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Hypothesis Explaining Muzzle Breaks

K.L. and B.J. Kosanke

ABSTRACT

Muzzle breaking aerial shells continue to be a significant cause of serious injury for persons discharging display fireworks. The problem is greatest for manually fired displays, where the person igniting the fireworks remains in close proximity to the mortar. Over the years, many possible causes for muzzle breaks have been suggested. Unfortunately, most of these explanations are incapable of withstanding close scientific scrutiny, and there has been no published study that has tested any of the potential explanations. Without knowing the cause(s) for muzzle breaks with some certainty, it is difficult (or impossible) for a manufacturer of aerial shells to know what measures might be taken to reduce or eliminate the chance of their occurrence.

Probably the best known characteristic of muzzle breaks is that they occur almost exclusively in the largest diameter (most potentially dangerous) aerial shells. Probably at least 90% of muzzle breaks occur in aerial shells 205 mm (8 in.) or larger. This is true, even though at least 90% of all aerial shells fired are smaller than 205 mm (8 in.). Thus any theory for the cause of muzzle breaks must account for this observation. The authors hypothesize that either setback or very small fire leaks lead to the occurrence of muzzle breaks, and that the dynamics of the propulsion of fireworks from mortars and the explosion of aerial shells is such that the chances for muzzle break occurrence is greatest for large diameter shells. In an attempt to test the hypothesis, a series of measurements were performed to determine the exit times of aerial shells from mortars and the times to explosion of shells after internal ignition. Results of these measurements are each somewhat surprising; they tend to support the hypothesis and provide insight into the mechanisms of aerial shell flowerpots.

Introduction

It is fortunate that, when manually igniting fireworks aerial shells using proper procedures, most of the common aerial shell malfunctions should allow the display crew to escape serious injury. For example, “flowerpots”, which are relatively weak explosions of shells inside mortars, should not result in crew injuries if: the mortars are angled away from the crew, shell loading is not being performed immediately adjacent to shell firing, minimal personal protection is worn, and the ready box (shell storage container) is covered and located upwind from the mortars. It is unfortunate that there are two less common types of aerial shell malfunctions for which proper procedure does not offer much protection against serious crew injuries. These two malfunctions are: 1) “shell detonations” (so-called, but probably not true detonations), which are powerful shell explosions inside mortars, in which the entire energy of the pyrotechnic contents of a shell is released essentially instantly, and they are powerful enough to generally destroy the mortar, hurling debris in various directions; and 2) “muzzle breaks”, which are explosions of aerial shells just after leaving the confinement of the mortar, and which propel shell casing fragments and burning contents in all directions at great speed.

The first step in the process of eliminating these two more dangerous types of shell malfunctions is the identification of the mechanism for their occurrence. Unfortunately, while speculation abounds as to the causes, there has been no systematic study published that confirms or dispels them. In this paper, a hypothesis explaining muzzle breaks is proposed, data collected to test that hypothesis is presented, and the results are discussed.

Background

In the past, theories have been advanced to explain muzzle breaks. Among the suggested causes are:

1) Extremely fast burning time fuse on the aerial shell;

2) Inertial effects that cause ignition of the shell when the contents radically shift position as the shell exits the mortar. (At this time, the shell experiences its maximum deceleration after having just experienced its maximum acceleration.),[1] and

3) Partial vacuums, created inside shells from lift gases rapidly flowing past a small hole on the exterior of a shell while it is still inside the mortar, and which then act to suck fire into the shell as it exits the mortar.[2]

There is one well-known characteristic of muzzle breaks for which any proposed theory must account. That characteristic is, having normalized for the numbers of various sized shells fired, almost all muzzle breaks occur with shells 205 mm (8 in.) and larger. For the most part, none of the above three theories successfully account for this characteristic.

1) Fast fuse: There is no reason to suppose that extremely fast burning time fuse is only used on large diameter aerial shells.

2) Inertial effect: Published data for spherical aerial shell muzzle velocities suggest that there is little or no systematic difference that is shell size dependent.[3,4] Since small diameter shells experience the greatest deceleration immediately after leaving the mortar, it might be expected that small diameter shells would experience the greatest normalized frequency of muzzle breaks.

3) Partial vacuum: A combination of published and unpublished data suggests that while mortar pressures tend to increase with shell size, relatively small diameter cylindrical shells experience the same mortar pressures as large diameter spherical shells.[4,5] Thus there is no reason to suppose that large diameter shells, which tend to be exclusively spherical shells, would be more prone to experiencing this problem than small cylindrical shells. In fact, based on their manner of construction, it is more likely that cylindrical shells (thus, small shells) are more likely to have a small hole in the proper location to cause this malfunction. Finally, an unpublished study suggests that the partial vacuums that can be created in this manner are probably too weak to cause fire to be sucked into the shell upon exiting the mortar.[6]

Because of the apparent difficulties with the above theories, it seemed useful to contemplate whether any other explanations could be advanced that were more consistent with the observation that muzzle breaks predominantly occur in large diameter aerial shells. Below, after some additional background discussion, is a hypothesis that fits this observation.

When an aerial shell, with an electric match installed in its lift charge, is fired from a mortar, it appears that the firing is instantaneous upon energizing the electric match. Obviously, however, that is not the case. Time is required for the ignition of the electric match; more time is required for flame to spread through the lift charge and for mortar pressure to build; finally time is required for the aerial shell to be accelerated up the mortar. Similarly, when a small flame, such as from an electric match, is introduced into an aerial shell, it appears that the shell explodes instantaneously upon energizing the electric match. But again, this is obviously not the case, as it takes time for the flame to propagate through the volume of the shell and for pressure to build to the point of exploding the shell casing.

The total internal volume of spherical aerial shells increases as the cube of the inner diameter of the casing. Presumably, the total void space between the internal components in the shell also increases roughly in proportion with the total volume. Because of the larger void space, it should take longer for the pressures to build to the point of explosion. Also, because of increased linear dimensions, it should take longer for flame to spread through a large aerial shell. Thus, large diameter aerial shells should require more time to explode than a small shell, after the introduction of a tiny flame.

In the context of muzzle breaks: ignition of the contents of the shell could be caused as the result of a small fire leak in some part of the shell; or from friction sensitivity of internal components producing a point of ignition during the acceleration of the shell (“setback”).

Based in part on the observation that the muzzle velocities of aerial shells are largely independ-

Table 1. Inert Aerial Shell Characteristics and Air Temperature during Tests.

Test No.	Shell Size mm	(in.)	Actual Shell Diameter cm	(in.)	Shell Mass g	(oz)	Lift Mass g	(oz)	Approx. Air Temp. °C	(°F)
Spherical Shells:										
7	76	(3)	6.6	(2.61)	135	(4.8)	28	(1.0)	27	(80)
4	102	(4)	9.5	(3.74)	360	(12.7)	28	(1.0)	21	(70)
9	102	(4)	9.5	(3.74)	335	(11.8)	46	(1.6)	21	(70)
11	127	(5)	11.9	(4.68)	625	(22.1)	50	(1.8)	27	(80)
10	155	(6)	14.4	(5.66)	1140	(40.3)	85	(3.0)	24	(75)
13	205	(8)	19.3	(7.60)	2700	(95.4)	155	(7.1)	21	(70)
12	205	(8)	19.3	(7.60)	2700	(95.4)	200	(7.1)	24	(75)
Cylindrical Shells:										
2	76	(3)	6.7	(2.64)	125	(4.4)	28	(1.0)	4	(40)
6	76	(3)	6.7	(2.64)	125	(4.4)	28	(1.0)	27	(80)
5	76	(3)	6.7	(2.62)	180	(6.4)	28	(1.0)	27	(80)
8	102	(4)	9.2	(3.62)	500	(17.7)	50	(1.8)	27	(80)
3	102	(4)	9.2	(3.62)	500	(17.7)	50	(1.8)	35	(95)
1	155	(6)	14.1	(5.56)	1870	(66.1)	125	(4.4)	4	(40)

ent of shell size,[3,4] it is worth speculating whether the times to exit for large shells are significantly greater than for small shells. If there is not much difference in the exit times, there is a possible basis for explaining muzzle breaks. That is to say, it is possible that muzzle breaks occur almost exclusively in large diameter shells, because:

- Mortar exit times for aerial shells are independent, or only weakly dependent, on shell size;
- While times to explosion of large shells are substantially longer than for small shells.

Thus after introduction of a point of ignition inside a shell:

- Small shells are more likely to explode while they are still inside the mortar (as a flowerpot);
- Whereas at least some large shells have time to exit the mortar before they explode (as a muzzle break).

In order to determine whether this hypothesis has any merit, it is necessary to know something about mortar exit times as a function of shell size, and of the times to explosion of aerial shells as a function of shell size. Because there is no published data of this type, and because such data is interesting beyond the context of this muzzle break hypothesis, the authors undertook a project to generate some of that information.

Aerial Shell Mortar Exit Times

Mortar exit times were measured for 76- to 205-mm (3- to 8-in.) spherical aerial shells, and for 76-, 102- and a few 155-mm (3-, 4- and a few 6-in.) cylindrical shells. In almost all cases, six identical shells were fired and the results averaged. All aerial shells were fired using an electric match (Davey Bickford N 28 B) installed into the lift charge. The current applied to the electric match, ≈6 amperes, is sufficient to have caused their ignition in less than 1 ms (0.001 second).[7] In all cases: the aerial shells were inert; the lift charge was placed in a small plastic bag attached to the bottom of the shell; the lift charge caused the shell to rest about 2.5 cm (1 in.) above the bottom of the mortar, except for the 205-mm (8-in.) shells where the larger lift bag held the shell about 3.8 cm (1.5 in.) above the bottom of the mortar. Characteristics of the sets of aerial shells used in these tests are presented in Table 1. Generally, shell and lift masses chosen for the test shells are averages of measurements made on collections of 10 to 20 live shells of one size but from various manufacturers.

In these tests, only inert shells were fired. This is because: it was intended that the same data be used for other purposes, in which the total flight times of the shells are needed; the cost of about 80 aerial shells ranging up to 205 mm (8 in.) was prohibitive; during most of the testing there was a ban on open burning, including fireworks, because of extreme fire danger in Colorado. In only two tests of 76-mm (3-in.) cylindrical shells, were the shells made of paper; all other shells had smooth plastic exteriors. Also, with Chinese aerial shells, one is never quite certain what quality lift charge has been used. Accordingly, to increase the likelihood that these results are consistent with those that would have been found for typical live shells, the lift powder used was a mixture of lift powder previously salvaged from oriental shells. It had a granulation ranging from about 4F to 6F. The lift powder for all the cylindrical shells was Goex 2F A-blasting powder.

The characteristics of the mortars used in the tests are shown in Table 2.

Table 2. Steel Test Mortar Characteristics.

Size		Diameter		Length	
mm	(in.)	cm	(in.)	cm	(in.)
76	(3)	7.9	(3.11)	50.8	(20.0)
102	(4)	10.3	(4.05)	60.7	(23.9)
127	(5)	12.9	(5.09)	75.9	(29.9)
155	(6)	15.4	(6.08)	75.7	(29.8)
205	(8)	20.3	(8.01)	90.9	(35.8)

For increased reliability, two different methods were used to determine aerial shell exit times. One method involved the measurement of the shells' muzzle velocity, using the times at which a series of trip wires are broken after the shells leave the mortar.[4,8] Figure 1 is a photograph of a test mortar with colored tape indicating the location of the trip wires. The trip wires are thin (0.48 mm) plastic insulated copper wires, stretched between electrical contact points. The wires are somewhat loosely secured at their ends, such that the wires typically pull free before stretching and breaking as the shell passes. Figure 2 shows the electronics package which fires the electric match in the lift charge and then provides the timing as each wire is broken. The unit was constructed by Pyrotech International specifically for this purpose and has a timing resolution of 0.1 ms. The first trip wire is 0.30 m (1 ft) above the mouth of the mortar, and the others are at 0.61-m (2-ft) intervals. Having determined each shell's muzzle velocity, and having measured the time to the first wire break, exit times can easily be calculated with a precision of a few milliseconds. Because of uncertainty as to the amount of wire flexing before pulling free or breaking, the accuracy of these measurements is probably several milliseconds.

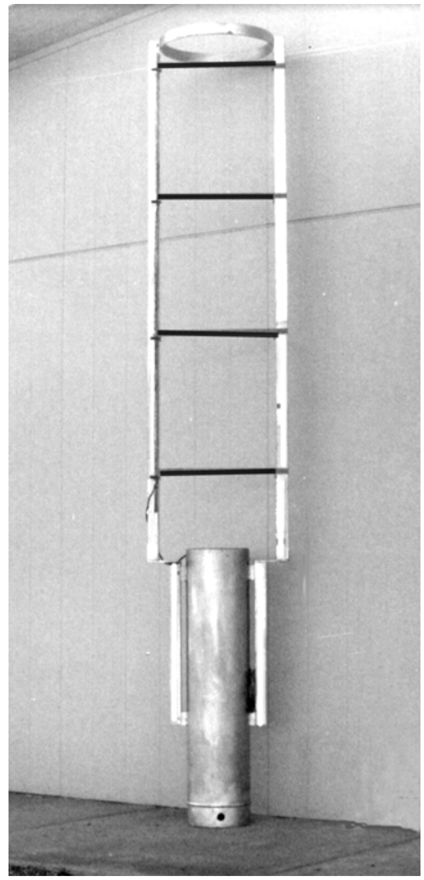

Figure 1. Photograph of a test mortar with colored tape indicating locations of trip wires.

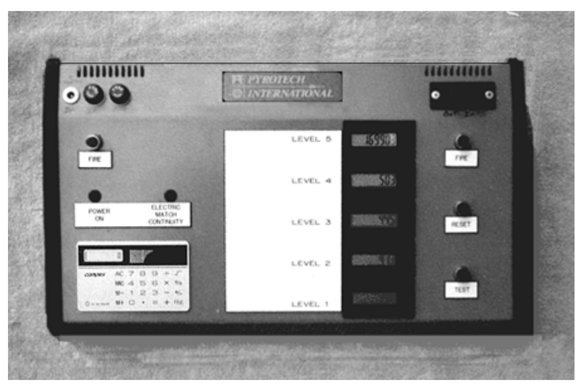

Figure 2. Photograph of the electronic firing and timing unit.

The second method used to measure exit times was to monitor the gas pressure profile in the mortar as the shell fires.[4] Mortar pressures were monitored using a quartz pressure sensor (PCB 101A04) and the data stored digitally, usually with a sampling rate of 5000 readings per second.

The pressure sensor was mounted in the center of the steel plate that closes the bottom of the mortar, much like was done in Reference 4. Figure 3 is a typical pressure versus time curve. A break in the pressure curve can be seen as the shell exits the mortar and the pressure drops more rapidly to one atmosphere. Since the digital oscilloscope was triggered by the energizing of the electric match, and knowing the oscilloscope time base setting, the exit time for the shell can be read directly from a print out of the data. Technically, the pressure measured at the sensor drops a short time after the shell actually leaves the mortar. However, because of uncertainty as to the speed of sound in the high temperature mortar gases, and because the correction would only be about one millisecond, no correction was made for this in the shell exit times. The precision of this method is about a millisecond, and the accuracy is probably no more than a few milliseconds.

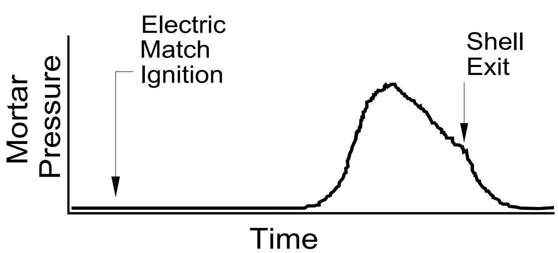

Figure 3. Typical mortar pressure versus time curve for a shell firing.

It is a little surprising that for about 60% of the time taken for the shell to exit the mortar, the pressure in the mortar remains near zero (see Figure 3). It seems likely this is correct, because there was good agreement between the two exit time measurements. Also, in a series of tests to measure the time for small electrically ignited salutes to explode, it was confirmed that the electric matches were functioning in significantly less than 2 ms. Apparently, during the initial near zero pressure part of the graph, the flame is spreading through the lift charge. Then, only after most of the powder is ignited and producing gas in the partial confinement of the mortar, does the pressure rise significantly above zero. (If interested, see Reference 9 for a more complete discussion of the effect of pressure and confinement on burn rate.)

Generally there was good agreement between the two different methods of measuring shell exit times. However, there were occasional problems with the trip wire data caused by debris (mostly electric match wires) exiting before the shell. Also, on a few occasions, the pressure data was noisy, because combustion residue had collected on or had blocked the pressure sensor, making it impossible to accurately identify the exit time of a shell. On a couple of other occasions the time base setting or trigger level setting of the oscilloscope was such that pressure data was not recorded. When the pressure data was of high quality, that was used to determine exit times, and the trip wire data was only used as confirmation. When there was any problem with the pressure data, exit times were determined from the trip wire data. The average results for aerial shell exit times are presented in Table 3.

In Tests 4 and 9 on 102-mm (4-in.) shells, the primary difference was that the amount of lift powder was increased from 28 to 46 g. This increase in the amount of lift powder resulted in a decrease in average shell exit times from 51 to 36 ms. In Tests 12 and 13 on 205-mm (8-in.) shells; the only difference is that the amount of lift powder was decreased from 200 to 155 g. This decrease in the amount of lift powder resulted in an increase in shell exit times from 31 to 38 ms. This is consistent with what might have been predicted; it is mentioned here because it illustrates that the data are sensitive to the shell parameters chosen for the inert test shells. Because shell and lift masses were averages from collections of live shells from various manufacturers, and because flight times of these test shells were in good agreement with earlier measurements made on live shells, it is felt that the performance of the test shells is similar to that which would have been obtained, had live shells been used.

Table 3. Aerial Shell Exit Time Results.

Test No.	Shell Size mm	(in.)	Exit Times (ms)	Average Exit Time (ms)	Remarks
Spherical Shells:					
7	76	(3)	42, 70, 34, 35, 27, 62	45	
C7	76	(3)	32, 70, 34, 35, 27, 62	43	Corrected, See Below
4	102	(4)	70, 48, 52, 34, 52, 48	51	28g Lift
C4	102	(4)	53, 48, 52, 34, 52, 28	48	Corrected, See Below
9	102	(4)	40, 28, 42, 30, 37, 37	36	46g Lift
11	127	(5)	56, 33, 45, 46, 37, 37	42	
10	155	(6)	34, 43, 36, 32, 47, 42	39	
13	205	(8)	34, 45, 36, 32, 45, 34	38	155g Lift
12	205	(8)	32, 25, 35, 32, 32	31	200g Lift
Cylindrical Shells:					
2	76	(3)	54, 103, 89, 58, 88, 76	78	125g Shell, Temp. ≈4 °C
6	76	(3)	70, 28, 39, 30, 26	39	125g Shell, Temp. ≈27 °C
C6	76	(3)	53, 28, 39, 30, 26	35	Corrected, See Below
5	76	(3)	36, 32, 38, 36, 52, 42	39	180g Shell, Temp. ≈27 °C
C5	76	(3)	23, 32, 38, 36, 52, 42	37	Corrected, See Below
8	102	(4)	40, 30, 30, 37, 27, 35	33	Temp. ≈27 °C
3	102	(4)	64, 29, 35, 37, 36	40	Temp. ≈35 °C
C3	102	(4)	49, 29, 35, 37, 36	37	Corrected, See Below
1	155	(6)	≈100, ≈40, 62	67	Temp. ≈4 °C

The test results for 76- and 102-mm (3- and 4-in.) cylindrical shells seem to be a little shorter than those for spherical shells. This seems to be consistent with what might have been predicted for shells whose shape provides less "loading space" (also called "dead volume"). However, data should be collected for larger cylindrical shells before concluding for certain that cylindrical shells typically have shorter exit times.

Some firings occurred during winter while collecting data for other purposes. The exit times from these tests are substantially longer than those measured in tests performed during the summer. This suggested a significant temperature effect, consistent with what was reported by others for mortar pressures.[10] However, in a pair of tests, 3

Table 4. Shell Exit Time Deviations from the Average.

Test Series	Exit Time Deviations (%) 1	2	3	4	5	6	Shell Type
3	60	–28	–12	–8	—	–10	102 mm Cyl.
4	37	–60	2	–33	2	–6	102 mm Sph. (28 g)
5	–8	–18	–3	–8	33	8	76 mm Cyl.
6	79	–28	0	–23	–33	—	76 mm Cyl.
7	–7	55	–24	–22	–40	38	76 mm Sph.
Ave. 3–7	32	–5	–7	–19	–10	–2	
8	18	–9	–9	12	–18	6	102 mm Cyl.
9	11	–22	17	–17	3	3	102 mm Sph. (46 g)
10	–13	10	–8	–18	21	8	155 mm Sph.
11	33	–21	7	10	–12	–12	127 mm Sph.
12	—	3	–19	13	3	3	205 mm Sph. (200g)
13	–11	18	–5	–16	18	–11	205 mm Sph. (155g)
Ave. 8–13	8	–4	–3	–3	2	0	

and 8, run on identical test shells, but at temperatures differing by 8 °C (15 °F), contrary to what was expected, the exit times for the higher temperature shells were slightly longer. Thus, at present, it is not clear what the temperature effect is on aerial shell exit times. Nonetheless, in an attempt to minimize any temperature effect, all data used to test the muzzle break hypothesis was collected between 21 and 27 °C (70 and 80 °F).

While performing the tests, it seemed as though another temperature effect was influencing the results. It seemed that the first few shell firings had significantly longer shell exit times than later firings. It was suspected that this might be the result of the mortar heating from the shell firings, which, in turn, was causing a heating of the lift charge of the next shell being loaded into the mortar. Accordingly, to limit any effect this was having on the data, beginning with test series 8, as little time as possible (only 4 to 6 seconds) was allowed to pass between loading and firing the test shells. The data in Table 3 was later examined to determine if this effect was real. For each of the identical shells fired in each test series, the exit time observed for that shell was compared to the average for the group of shells. The deviation from the average was expressed as a percentage, with positive numbers corresponding to exit times longer than the average and negative numbers, less than average. Next, the results for each of the 6 shells from test series 3 through 7 were averaged, and the same was done for the shells in test series 8 through 13. The results are shown in Table 4.

Note that:

- The first shell fired in test series 3 through 7 had an exit time that averaged 32% longer than average.
- All other shells in test series 3 through 7 had exit times less than average.
- The first shell fired in test series 8 through 13 had an exit time that averaged 8% longer than average.

Accordingly it can be concluded that:

- The mortar temperature effect primarily affected the first shell firing in each series.
- The corrective action, minimizing the time in the mortar before firing, mostly corrected the problem.

In order to have a more consistent set of data, it was decided to adjust the shell exit times for the first shell fired in test series 3 through 7. This was accomplished by reducing those shell exit times by 24%, the difference between 32 and 8%. These values are included in Table 3, with a "C" prefix to the test number and the remark "Corrected, See Below". Note that the average shell exit times were lowered about 3 ms as a result of making this correction.

Figure 4 is a presentation of the aerial shell exit times data for spherical shells, using corrected times for test series 4 and 7. The trend line for the data is the linear least square fit. It appears certain that shell exit times do not increase with increasing shell size. Further, and surprisingly, it seems likely that shell exit times actually decrease slightly with increasing shell size. Near constant or decreasing times are consistent with what would be necessary for the muzzle break hypothesis proposed above.

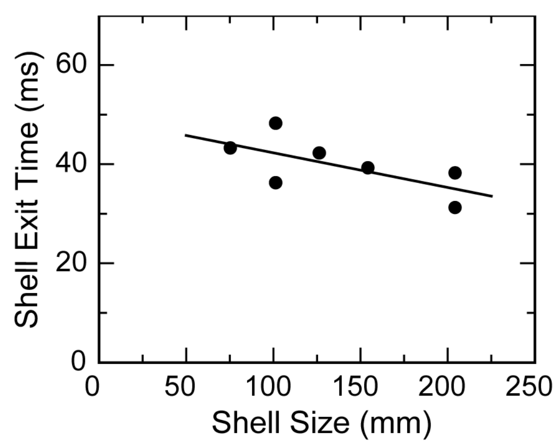

Figure 4. Graph of spherical aerial shell exit time as a function of shell size.

Aerial Shell Burst Delay Times

Burst delay times were measured for spherical aerial shells ranging in size from 76 to 255 mm (3 to 10 in.). The shells were ignited using an electric match inserted into the shell. This was accomplished by making a small hole, only slightly larger than the electric match, by remotely pressing a pointed tool through the shell casing, a little above or below the equator of the shell. The tip of the electric match was inserted about 1.5 cm (0.6 in.) into the shell. The hole was closed using three layers of strapping tape encircling the shell in different directions. As a sensor to indicate the bursting of the shells, two loops of wire encircling the shell were used. The loops crossed the poles of the shell at about a 90° angle. These wires were held in position using small dabs of hot-melt glue along its length. The configuration of a typically prepared test shell is shown in Figure 5. To make the measurement, the test shell was suspended above the ground, and then electrically attached to the timing and firing apparatus. The electric match was energized with sufficient current to cause its ignition in less than one millisecond. The contents of the shell were thus ignited, causing the shell to burst (explode). As the casing expands and fragments, the loops of wire break. Figure 6 is a photograph of one of the tests using a 205-mm (8-in.) aerial shell. Burst delay times were determined using an electronic timer to measure the time between application of current to the electric match and when the wire loops break. The same apparatus was used in these measurements that had been used earlier to determine the times of breaking of the trip wires.

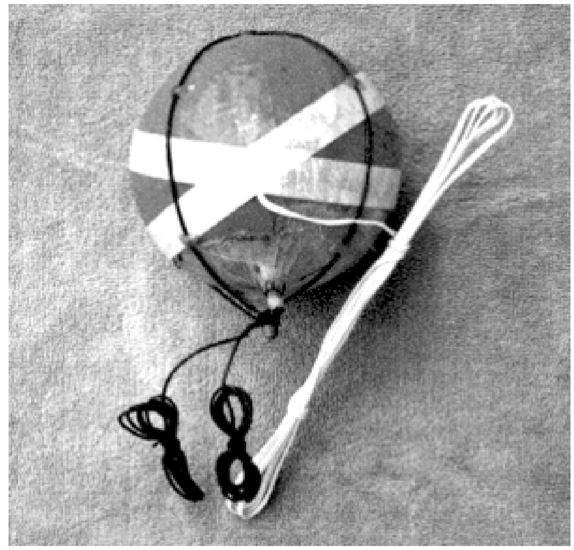

Figure 5. A typically prepared shell used in measuring burst delay times.

For the burst delay times to be representative of typical shells, the shells used in these measurements came from seven different manufacturers. These manufacturers were: Yung Feng (Y), Horse (H), Temple of Heaven (T), Onda (O), Red Lantern (R), Sunny International (S), and Flying Dragon (F). In the data presented below, the manufacturer is identified using the code letter listed for each manufacturer. Burst delay times are presented in Table 5.

It would have been preferred to have tested a larger number of shells, and to have used a wide and consistent set of manufacturers for each shell

Figure 6. A photograph of the test of a 205-mm (8-in.) Aerial shell.

Table 5. Aerial Shell Burst Delay Times.

Shell Size			Average Delay Time
mm	(in.)	Burst Delay Time (ms) / Manufacturer	ms
76	(3)	30/S, 32/S, 36/Y, 41/S, 48/T, 76/H, 122/T	43[(a)]
102	(4)	21/S, 44/Y, 50/R, 51/H, 53/R, 78/T, 81/S, 104/R	54[(b)]
127	(5)	26/S, 40/S, 59/O, 62/R, 73/T	52
155	(6)	54/H, 55/S, 77/T, 82/F, 89/T	71
205	(8)	52/Y, 96/Y, 329/H	74[(c)]
255	(10)	134/O	134

(a) The burst delay time of 122 ms was not included in the average.
(b) The burst delay time of 104 ms was not included in the average.
(c) The burst delay time of 329 ms was not included in the average.

size. However, this was not possible because of economic constraints.

While most of the burst delay times for each shell size are fairly well grouped, there are occasional values that are significantly longer than the rest of the group. The most extreme example is the delay time for the Horse brand 205-mm (8-in.) shell, which was 329 ms as compared with 52 and 96 ms for the other two shells. Similarly was the 122 ms for the 76-mm (3-in.) Temple of Heaven shell and the 104 ms for the 102-mm (4-in.) Red Lantern shell, are significantly longer than the burst delay times for the other shells in the groups. It is felt that these longer delay times were real. This is because, in each of these three cases, the time interval, between pressing the button to energize the electric match and when the shell explosion occurred, was noticeably longer than for the other shells. The cases of longer than normal burst delay times may represent some type of anomalous ignition of the shells' contents, in which the fire transfer from the match was substantially less effective than in the other cases. This notion is supported by the fact that in two other cases, although the electric match fired normally inside the shell, the contents were not ignited and the shells failed to explode. In both cases, a second attempt produced a shell explosion with the delay time typical for shells of that size. In order to not bias the data by including the abnormally long burst delay times, they were excluded when calculating the average delay times for each size shell.

Average shell burst delay times, as a function of shell size, are presented in Figure 7. In the linear least squares fit to the data, the average delay times were weighted according to the number of shells of each size that were included in the average. In Figure 7, it is apparent there is a significant increase in burst delay times for larger shells. This is consistent with what is necessary to support the proposed muzzle break hypothesis.

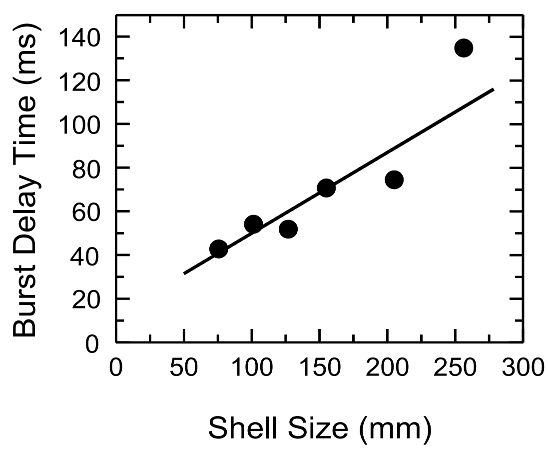

Figure 7. Average Shell Burst Delay Times as a Function of Shell Size.

Discussion

The trends in both the shell exit time and burst delay time data are consistent with the hypothesis presented as a possible explanation for muzzle breaks. However, there are two time related matters that need to be examined more closely. Figure 8 is a graph of the least squares fits to the data presented in Figures 4 and 7. According to the hypothesis presented, muzzle breaks occur when aerial shells (whose contents become ignited by a fire leak or from inertial setback) exit the mortar before they have time to explode. Recognize that the two lines in Figure 8 only represent average times as a function of shell size and that individual shell exit times and burst delay times vary widely about these averages. Figure 8 correctly predicts that muzzle breaks are more likely for large shells. However, it incorrectly predicts that, for most in-mortar shell ignitions, the shell will exit the mortar before it explodes (i.e., it incorrectly predicts that muzzle breaks are more likely than flowerpots). For example, the average exit time for a 127-mm (5-in.) shell is about 40 ms and the average burst delay time is about 50 ms. Accordingly, for shells fired and ignited internally as in these tests, a typical 127-mm (5-in.) shell will have left the mortar about 10 ms before it explodes as a muzzle break (50 – 40 = 10).

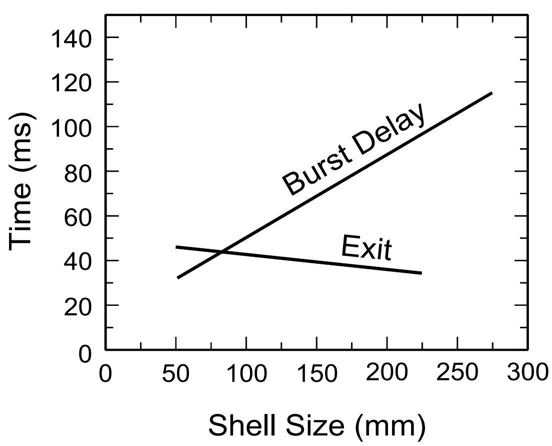

Figure 8. Average mortar exit and burst delay times as a function of shell size.

The apparent inconsistency identified in the last paragraph must be dealt with; however, before doing so, consider the following additional problem. An internal ignition of an aerial shell, either as a result of small fire leak or inertial setback, will not occur until the pressure in the mortar has risen significantly above atmospheric pressure. Without significant mortar pressure, burning gases will not be forced into tiny crevices or holes in shell casings, or glue seals around time fuses. Without significant mortar pressure, the shell will not be accelerating and there will not be a setback effect. Note in Figure 3 that the first indication of mortar pressure rise does not happen until at least half the time has passed between electric match ignition and the shell exits the mortar. This just serves to exacerbate the apparent timing inconsistency mentioned in the last paragraph. The fire that eventually causes the shell to explode is not introduced at the same time as the electric match fires in the lift, but rather, only after about half the shell exit time has elapsed. Accordingly, for the typical 127-mm (5-in.) shell, with an exit time of about 40 ms and a burst delay time of about 50 ms, the times do not start together. The 50 ms burst delay time does not start until the mortar pressure begins to rise about half way through the shell firing process. Thus, for shells fired and ignited internally using the method of these tests, the shell will have exited the mortar 30 ms before it explodes (50 – 40/2 = 30). If this is correct, then the question should be, why do not essentially all in-mortar internal shell ignitions result in muzzle breaks, almost to the exclusion of flowerpots?

The discussion that follows is supposition, in that no supporting data was collected. Hopefully, however, the discussion is based on a combination of well established pyrotechnic principals and logic. For pyrotechnic material, the rate of flame spread depends on the level of ignition stimulus. Accordingly, a powerful ignition stimulus, such as a small explosive charge, is expected to cause more rapid flame spread through a pyrotechnic composition than would ignition of the same material from contact with a hot wire. When the contents of an aerial shell are ignited, and if the rate of flame spread is high, material will be ignited more quickly, producing gaseous combustion products more quickly, and bursting the shell sooner. Accordingly, it would be expected that aerial shell burst delay times are dependent on the level of ignition stimulus used, with shorter delay times expected for more powerful stimuli.

Consider the following scale of ignition stimuli. On the weak stimulus end is ignition as a result of a pair of stars in a shell rubbing together during setback. On the strong stimulus end is ignition caused by the time fuse pushing into the shell, opening a large hole and allowing the entrance of a large amount of burning lift gas. The ignition of an electric match produces a significant flame and radiating sparks. (The Davey Bickford product brochure[11] illustrates the output of an electric match.) On the above crude ignition stimulus scale, the ignition stimulus provided by an electric match, must be somewhere near the middle. Accordingly, it would be expected that the possible sources of ignition of the contents of aerial shells within mortar would result in average burst delay times both longer and shorter than those observed in this study using electric matches.

During the firing of an aerial shell, any ignition stimulus, equal to or weaker than that of an electric match, would be expected to almost exclusively produce muzzle breaks. This is because such ignition stimuli should result in burst delay times equal to or longer than those reported in this study, which are already long enough to produce mostly muzzle breaks. It is only those ignition stimuli that are significantly stronger than that produced by an electric match that would be expected to produce flowerpots.

Conclusions

1) It is somewhat surprising that: mortar pressure does not begin to rise significantly until about half the shell exit time has elapsed; and large aerial shells appear to have shorter exit times than small shells.

2) Since flowerpots greatly out number muzzle breaks, this study suggests that most causes of in-mortar ignition of the contents of aerials shells must be produced by powerful ignition stimuli. This would include, catastrophic shell casing failure as might be caused by too weakly constructed shells or by shells that jam inside the mortar. Another possibility is that time fuses are being removed because they have been pushed into shells by high pressure lift gases, or that they are perhaps pulled loose as a result of spherical shells rotating while traveling up the mortar. Still another possibility is that the powder in the time fuse is loose and allows the high pressure lift gases to blow through, directly into the shell.

3) On average, any weak ignition stimulus, such as ignition caused by inertial setback, is expected to only produce muzzle breaks, not flowerpots.

4) The range of mortar exit times for sets of identical shells is surprisingly wide. Typically the longest time is two to three times the shortest time. This suggests that the dynamics of flame spread and combustion are highly variable from shell firing to shell firing.

5) Significantly longer average exit times were observed for the two low ambient temperature data sets and for the first shell fired in each data set. This is consistent with temperature effects observed by others.[10] Further, this suggests that muzzle breaks may be statistically more likely during manually fired displays when there are repeat firings from the same mortar during a display.

6) The range of shell burst delay times for shells from a variety of manufacturers is surprisingly wide. Typically the longest time is two to three times the shortest. However, on occasion, the longest is five or six times the shortest. In part this is probably due to differences in the pyrotechnic materials and the construction techniques used. However, as in Conclusion 4, it is likely this is also the result of significant variability in the dynamics of flame spread and combustion.

7) Further studies should be performed to confirm these data and to better identify the causes of muzzle breaks and flowerpots. Some additional work is planned by the authors; specifically, examining the effect of greater and lesser ignition stimulus on shell burst delay times. However, others are encouraged to input to the discussion of these results and to conduct additional studies.

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