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Preliminary Study of the Effect of Ignition Stimulus on Aerial Shell Lift Performance

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ABSTRACT

Based on the experience of a small fireworks display company with several low-breaking aerial shells, it was speculated that the cause might be related to having modified the aerial shell ignition system. To evaluate this possibility the effect of various levels of ignition stimuli on the performance of aerial shell Black Powder lift charges was briefly investigated. The purpose of the study was to scope the nature and magnitude of any resulting effects. Armed with that information it would then be possible to better design a more extensive study if needed.

Three levels of ignition stimuli were used: hot-wire igniters, electric matches, and fireworks quick match. Using identical test shells, upon firing, no statistically significant differences were found in their times of flight and mortar pressure impulses. Thus, either the low breaks were the result of something unrelated to ignition stimulus, or the statistically small number of trials was not sufficient to identify the effect.

Introduction

A few years ago, the owner of a small fireworks display company was experiencing what he felt was an abnormally large number of significantly low breaking shells (a few percent). These appeared to be the result of those shells being weakly propelled from the mortars. These were aerial shells of Chinese manufacture that had been modified by the display company for their use in electrically fired displays. The quick match shell leaders were removed and replaced with electric matches inserted directly into the lift charge. Obviously, one possible explanation for the low breaks was a deficiency associated with the lift charge of some of the shells. The deficiency could be simply an insufficient amount of Black Powder, or that the powder was of poor quality and thus burned too slowly to be fully effective. However, a few displays had also been performed where the quick match had not been removed, and during which there seemed to be many fewer low breaks. Accordingly, speculation about potential causes was expanded to include the possible effect of a relatively weaker ignition stimulus level being provided by an electric match in comparison to that provided by a jet of burning gas from a vigorously burning quick match shell leader.

Background

McLain has reported[1] that varying levels of ignition stimulus can produce differences in pyrotechnic output. To some extent, Shimizu also documents[2] the effect of varying the level of ignition stimulus. He reports that the velocity of propagation for flash powders can be substantially greater when initiated using a detonator (blasting cap) in comparison to that produced by thermal ignition. For example, a potassium perchlorate, aluminum, and sulfur flash powder (in a ratio of 70:27:3, respectively) propagated at approximately 870 m/s when an electric igniter was used, as compared with a rate of 1420 m/s when initiated using a number 8 detonator.

In addition to McLain's and Shimizu's reports, the authors' found indirect evidence suggesting that the internal ballistics of aerial shells

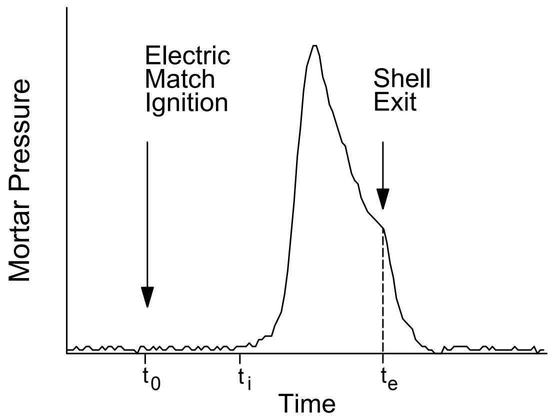

Figure 1. A typical mortar pressure profile during the firing of an aerial shell.

are quite sensitive to relatively minor changes in ignition stimulus. During laboratory measurements, it was found that surprisingly large variations in peak mortar pressure and muzzle velocity occur for apparently identical shell and lift powder configurations.[3–6] One possible explanation for this is that small differences occurring in the earliest stages of lift charge burning are responsible for relatively large differences in the propulsion of the aerial shells. Limited support for this theory can be seen in the lift pressure profile in a mortar as a shell is fired (lift pressure as a function of time). (See Figure 1.) For approximately half of the time (t_0 to t_i) between igniting the lift powder and the expulsion of the aerial shell (t_0 to t_e), there is no significant pressure rise. Presumably this apparently quiescent period is the time taken for the fire to spread through the grains of Black Powder before the burning becomes vigorous enough to cause a measurable rise in pressure. If that is the case, it is certainly possible that changing the manner of ignition of the lift powder could change the dynamics of the early fire spread and thus produce a significant difference in the propulsion of aerial shells. More support for this theory was found when it was discovered that lift performance can be significantly affected by relatively small changes in the point of ignition with all else being constant.[4]

With the firing of an electric match, there is a sudden burst of fire, which is fairly limited in both amount and duration. With burning quick match, potentially a much more substantial and sustained jet of fire is produced. Thus it seemed reasonable to speculate that quick match, especially the quite vigorous burning quick match found on some Chinese shells, would provide a greater ignition stimulus for the lift charge than that provided by an electric match. Further, because Chinese lift powders tend to be somewhat slow burning in comparison to domestically produced Black Powder, the Chinese powder might be expected to be more sensitive to the level of ignition stimulus.

However, to the contrary, if a weak ignition stimulus was the cause of the low break problem, then why did the problem not occur in many more of the Chinese shells being fired using an electric match? Further, why had other display companies, that also used electric matches installed directly into the lift charges, not been reporting similar problems? Despite these possible contrary indications, it seemed that the ignition stimulus hypothesis was worth further consideration; not only because it might be related to the low break problem, but also because it might help to explain the large variations in lift performance observed experimentally during the firing of what seemed to be identical aerial shells. Accordingly, a brief study was undertaken to investigate the effect of various levels of ignition stimulus on lift powder performance.

Experimental

In this scoping study, 3-inch (75-mm) aerial shells were used. This was for reasons of cost and because the display company felt that most of the low breaks occurred with small diameter shells. In the first part of this investigation the lift charges were harvested from three shells of each of the brands to be studied—Thunderbird, Sunny and Jumping Jack. In physical appearance, the Thunderbird and Jumping Jack powders were indistinguishable. Sieve analyses of the powers were performed, with the results shown in Table 1 and discussed below.

The general performance of lift powder for each shell brand was then evaluated using an apparatus designed to simulate the conditions during the firing of small aerial shells.[4] In this apparatus, a loose fitting projectile is fired from

Table 1. Sieve Analysis for Test Shell Lift Powders.

Powder Type	Percent in Mesh Fraction			
	+12	12–20	20–30	–30
Jumping Jack	33.8	66.0	0.2	0.0
Thunderbird	31.3	68.1	0.6	0.0
Sunny	0.0	46.8	46.9	6.3

(Mesh numbers are for US Standard Sieves.)

a test mortar fitted with a series of trip wires. Upon firing, the timing of the breaking of the trip wires was used to determine the speed of the projectile. In addition, the mortar pressure profiles were measured and digitally recorded. To accomplish a reliable comparison between the three powder types, in these tests, only their 12–20 mesh fractions were used. For each firing the charge mass was 5.0 g (0.18 oz), the temperature of the powder and combustion chamber was maintained at 80 ºF (27 ºC), the apparatus was in its normal configuration, and three test firings were conducted for each powder type. Averages for each set of three firings are presented in Table 2. In the reported results, "Delay Time" is the interval of time between the application of current to the electric match (t_0) and the first detectable rise in pressure in the mortar (t_i). (The firing time of the electric match under these conditions was previously measured to be less than 1 ms.) In Table 2, "Impulse Time" is the interval of time between the first detectable pressure rise (t_i) and when the projectile exits the mortar portion of the apparatus (t_e). Exit times were determined by the change in slope of the pressure curves (See Figure 1.) and verified by the trip-wire data. (These results are discussed below.)

The main portion of this study was the investigation the effect of varying levels of ignition stimulus on the actual firing of aerial shells. For these tests, the three methods of ignition were used. It is believed that the weakest ignition stimulus was that produced using a simple hot wire igniter. This was hand made using a short length of 26 gauge (American Wire Gauge) nichrome wire attached to 22 gauge copper leg wires. The next greater stimulus is thought to be that produced using an electric match (Daveyfire SA-2000). The third level of ignition stimulus, thought to be the highest level, was that produced by a length of quick match. In each case, the end of the igniter was introduced into the approximate middle of a small plastic bag of lift powder. To provide fairly constant geometry and dead volume, the bag of lift powder was placed in a small paper cup that was then taped to the bottom of the test shell.

To have a high degree of uniformity among the test aerial shells, the original shells were not used, rather nine inert shells were prepared for firing. Each test shell weighed 130 g (4.6 oz), was 2.62 in. (67 mm) in diameter, and was made of plastic. The amount and type of lift powder on the various test shells was the same as that used by the three shell manufacturers. There were 34 g (1.2 oz) of Thunderbird's lift used on three test shells, one each using the three ignition methods. Similarly, 25 g (0.9 oz) of Sunny's lift was used on three test shells, and 30 g (1.1 oz) of Jumping Jack's lift was used on three shells. (See Figure 2 for an illustration of the component parts of the test shells, including the three types of igniters.) The assembled test shells were fired at an ambient temperature of 55 ºF (13 ºC) from a steel mortar 3.10 in. (79 mm) ID, 24 in. (0.61 m) long, and instrumented with a piezoelectric pressure transducer.[7] The re-

Table 2. Average Performance Test Results for the Three Lift Powders.

Powder Type	Muzzle Velocity (ft/s)	Peak Pressure (psi)	Impulse Time (ms)	Delay Time (ms)
Jumping Jack	170	54	7.8	15
Thunderbird	170	52	7.7	17
Sunny	210	64	7.2	17

To convert feet per second (ft/s) to meters per second (m/s), divide by 3.29.
To convert pounds per square inch (psi) to kilopascals (kPa), multiply by 6.89.
Because of the limited number of trials, results are reported to only 2 significant figures.

sults from the three sets of three test firings are reported in Table 3. In each case, the time of flight (ToF) reported is the average of the times determined by two people using stop watches to determine the total flight times of the test shells. Peak pressure (P. Pres.) is the maximum pressure measured during each firing. Pressure impulse (Imp.) is the area under the pressure versus time curve for each firing up until the exit of the test shell.

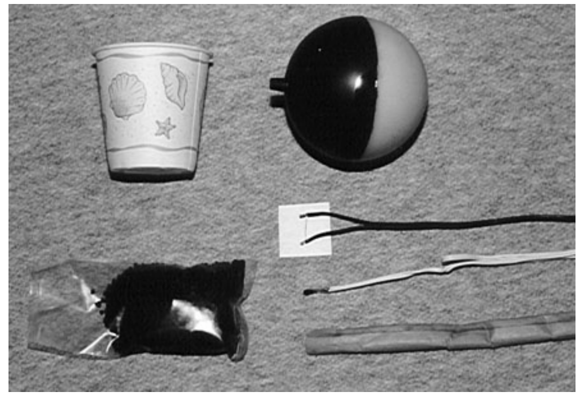

Figure 2. Photograph of the component parts of the test shells.

Discussion

Based on their physical appearance, particle size distributions (Table 1) and performance data (Table 2), it seems fairly likely that Jumping Jack and Thunderbird lift powders are from the same source. It also appears that the Sunny lift powder is a little more effective than the others and is probably why a somewhat smaller amount was used on the Sunny shells [25 g (0.9 oz) versus 30 g (1.1 oz) and 34 g (1.2 oz) for the Jumping Jack and Thunderbird shells, respectively]. As essentially identical ballistic bodies, the times of flight of the test shells are a good (although not a linear) indication of the relative heights reached by the shells. Further, for essentially identical test shells, pressure impulse is a good measure of the shell's muzzle velocity[5] and thus the height reached by the shells. The results from this limited series of trials are reported in Table 3 and offer no support for the hypothesis that the cause of the low breaking shells was the result of substituting electric matches for quick match into the lift charges. That is to say, to within the limits of statistical uncertainty in the data, no difference was found in the propulsion of the test shells for the presumed three levels of ignition stimulus used.

A fairly wide range of ballistic performance is observed even for apparently identical aerial shells.[3–6] Thus it is not expected that making a change in ignition stimulus would necessarily cause all the test shells fired with electric matches to be significantly under propelled. Further, with only three test firings, it certainly is possible that none would be significantly under propelled. Thus, while it is possible there is essentially no effect from using the three lift powder ignition methods, these results cannot be interpreted as being conclusive. However, as a minimum, the results identify that a more extensive study is needed (using more shells and

Table 3. Results from the Firing of the Series of Test Shells.

Shell Mfg.	Hot-wire			Electric Match			Quick Match		
	ToF (s)	P. Pres. (psi)	Imp. (psi s)	ToF (s)	P. Pres. (psi)	Imp. (psi s)	ToF (s)	P. Pres. (psi)	Imp. (psi s)
Thunderbird	7.6	26	1.2	7.8	23	1.2	7.9	26	1.3
Sunny	8.8	37	1.6	7.6	34	1.2	9.4	42	2.0
Jumping Jack	7.6	24	1.2	8.1	30	1.5	6.4	18	0.8
Average	8.0	29	1.3	7.8	29	1.3	7.9	29	1.4

Note that, "ToF" is aerial shell time of flight, "P. Pres." is peak internal mortar pressure, and "Imp." is pressure impulse acting on the aerial shell while it is in the mortar.

To convert pounds per square inch (psi) and psi-seconds (psi s) to kilopascals (kPa) and kPa-seconds (kPa s), multiply by 6.89.

Because of the limited number of trials, results are reported to only 2-significant figures.

possibly considering more potential explanations). It is hoped that a follow-on study will be undertaken in the future.

Acknowledgements

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References / Notes

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7) The pressure gauges were PCB Piezotronics 101A04, connected to PCB Piezotronics 480D06 amplifying power supplies. The data was recorded using Fluke Scopemeters model 95 or 97, then transferred to a computer for processing.