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Fireball Characteristics as Determined in a Test Simulating the Early Stage of a Fireworks Truck Loading Accident

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A few years ago there was an investigation and analysis of an accident thought to have been initiated by the ignition of a case of spherical aerial shells in the cargo area of a truck. It was thought that the case of shells had been dropped or thrown to the floor of the truck during the course of its loading. (Note that some of the facts of the matter may be in dispute.) As part of that investigation, it was thought that a simple test would aid in establishing the likely sequence of events during the early stages of the accident. Accordingly a test was performed to estimate the extent and rapidity with which the initial fireball would develop from the ignition of a case of spherical aerial shells. Because the information developed by the test is of general interest to persons working with display fireworks, this brief article has been written.

At the time of the accident, it was known what display was being loaded into the truck, including the total number and type of aerial shells, and the total number of cartons. However, it was not known what was in each carton or which of the individual cartons of aerial shells ignited first. Accordingly, the best that could be done was to assemble a test case of aerial shells containing the average number of each size shell (see Table 1) known to have been in the display.

Among the shells known to be present were a large number of Horse Brand shells, which had quick match shell leaders made using a combination of a long strand (or two) of Chinese style firecracker fuse along with black match. Unfortunately, the Chinese fuse powder contained a chlorate (presumably potassium chlorate) and the black match contained sulfur. It was thought that a likely explanation for the accidental ignition was the pinching of one of these shell leaders between two colliding shell casings as the carton impacted the floor of the truck. This somewhat violent pinching is suspected to have caused both a commingling of the chlorate and sulfur compositions, and the mechanical energy for their ignition. (The inherent dangers of chlorate and sulfur mixtures are quite well known.[1]) In an attempt to approximately simulate this manner of ignition, an electric match inserted into one of the shell leaders was activated to initiate the test. (Note that in the accident, it was reported that no electric matches were present.)

Table 1. Number and Size of Inert Shells Used, Including Estimates of the Amount of Lift Charge and the Length of Shell Leader.

Shell Size (in.)	No. of Shells	Lift Charge (oz)		Shell Leader (ft)	
		Per Shell	Comb.	Per Shell	Comb.
3	24	0.5	12	2.0	48
4	7	1.0	7	2.5	18
5	5	1.7	8	3.0	15
6	2	2.7	5	3.5	7
Totals	38	—	32	—	88

To convert approx. ounces to grams, multiply by 28.
To convert approx. feet to meters, divide by 3.3.

Following the ignition of the first carton of shells, there would have been a delay of approximately 3 to 5 seconds before the ignited time fuses would cause shells to explode. Further, because the collective burning of the shell leaders and lift charges in the ignited case would only have been very mildly explosive, it was thought that the ignition of the shells in the other cases would likely not have occurred until exposed to the fire for at least several seconds or, more likely, when the shells in the first case started exploding. Because of the likely delay of 3 to 5 seconds before the participation of additional pyrotechnic materials, the question attempting to be answered was: to what extent would the conflagration produced by just the shell leaders and lift charges in the first carton have tended to engulf persons working in the cargo area and impede them from exiting? Accordingly, the test shells were inert except for their leader fuses and lift charges. The shell leader lengths and lift charge amounts are also given in Table 1.

The ignition of the test case of shells and the progress of the ensuing conflagration was recorded using two video cameras, providing close-up and full views of the fire output. Figure 1 is a composite sequence of individual video fields recorded at times of 0.0, 0.2, 0.5, and 0.9 second after firing the electric match. Unfortunately, in a gray scale image such as in Figure 1, it is not possible to differentiate between the yellow/orange fire and the white smoke. Accordingly, for the purposes of this article, prior to converting the series of color images to gray scale, the approximate area of the fireball in each frame was outlined with a black line. In determining the extent of the fireball in each video image, it was the extent of the yellow/orange (fire) area that was used. Over the course of the images, the fireball is seen to drift to the left due to an approximate 4 mph (1.8 m/s) breeze in that direction. However, it is not thought that this significantly affected the results.

Using the full video record, the volume of the fireball was estimated after each 0.1 second time interval. First, an estimate of the projected area and length of the fireball was made. (The length of the fireball was determined as distance from the approximate center of its bottom to the approximate center of the highest extent of the fireball.) The projected area and length were determined through a comparison of the fireball with features in the background of known dimension, and considering the distances from the camera to the fireball and background. Then, assuming the shape of the fireball was approximately cylindrically symmetric about an axis running from the center of its base to its tip, calculations were performed to estimate its volume. Those volumes as a function of time are presented in Table 2 and as a graph in Figure 2. It was not known what the shape of the fireball volume curve should be expected to have. However, it was fit reasonably well by simply using two straight lines. (It is thought that a reasonable estimate for the uncertainty in the results being reported is 10 to 20 percent.)

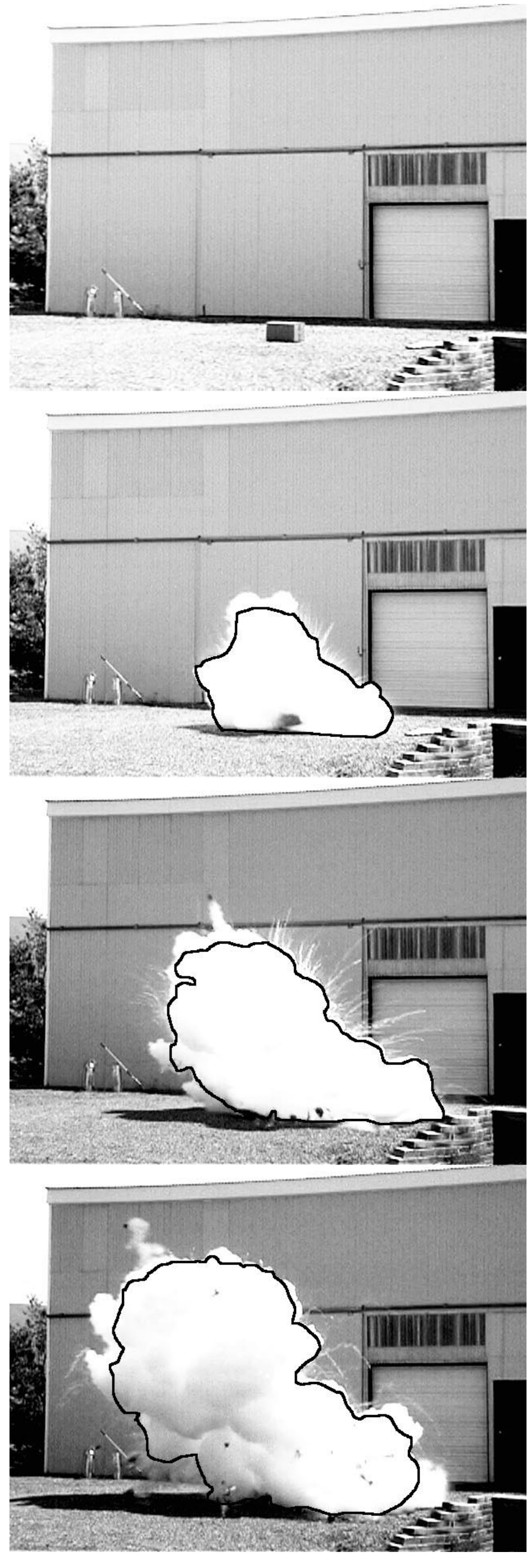

Figure 1. A collection of video fields recorded at times of 0.0, 0.2, 0.5, and 0.9 second after firing the electric match. The approximate extent of the fireball, as opposed to white smoke, has been outlined in each image.

Table 2. Estimates of the Volume of the Fireball Produced during the Course of the Test.

Time (s)	Volume (ft^3)	Volume (m^3)
0.1	50	1.4
0.2	250	7.1
0.3	380	10.8
0.4	480	13.6
0.5	560	15.9
0.6	750	21.3
0.7	780	22.1
0.8	970	27.5
0.9	1100	31.2
1.0	1100	31.2
1.1	940	26.6
1.2	790	22.4

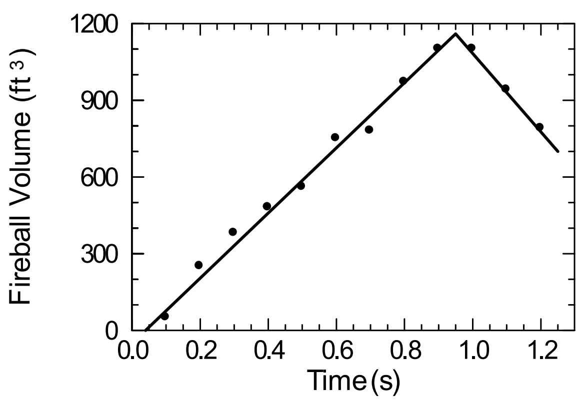

Figure 2. A graph of estimated fireball volume, as a function of time, fitted using two straight lines. (To convert from cubic feet to cubic meters, divide by 35.)

For the purpose of the accident investigation it was of interest to learn the extent to which the likely fireball, produced by the shell leaders and lift charges from this first case of aerial shells, would fill the open volume of the cargo area of the truck. In addition, it was of interest to discover whether there was any realistic probability that a person in the cargo area near the point of origin could exit prior to being engulfed within the fireball. This was of prime interest because it has been reported that for a person attired in normal clothing, such clothing will spontaneously ignite and the person will receive deep third degree burns, if engulfed by a pyrotechnically produced fireball.[2] Further, it is suggested ("assumed") that there is essentially no chance of a person's long term survival from having received such extensive burn injuries.[3]

If the height and width of the cargo area are each assumed to be 8 feet (2.4 m), based on the test results reported above, the approximate volume of the fireball is capable of completely filling a 17-foot (5.2-m) length of the cargo area. Further, this will occur in slightly less than 1 second, clearly much less than the time it would take for a person near the point of origin to exit the cargo area. (Indeed, in the accident under consideration, the two persons nearest the point of origin were fatally burned, and the two persons near the back of the truck escaped, although having sustained significant burn injuries.)

Before leaving this subject, it is of interest to compare the approximate results of this simple test using a case of simulated aerial shells, with the results for loose Black Powder reported in the literature (see Table 3). The results reported[4] for 1 kg (35 oz) of Black Powder are for a fireball with a diameter of 3.2 m (10.5 ft), a volume of approximately 17.6 m^3 (620 $feet^3$) and a duration of 1.0 second. In the current test, the fireball was produced by 32 ounces (0.91 kg) of Black Powder plus 88 feet (27 m) of quick match and black match, which contributed approximately 6 additional ounces (0.17 g) of powder. This produced

Table 3. A Comparison Between these Approximate Results and those Reported in the Literature.

Data Source	Powder Mass (oz)	Fireball Characteristics Diam. (ft)	Vol. (ft^3)	Duration (s)
Current Test	38[a]	12.7[b]	1100	1.6
Literature[4]	35	10.5	620	1.0

To convert approx. ounces to grams, divide by 28.

To convert approx. feet to meters, divide by 3.3.

To convert approx. cubic feet to cubic meters, divide by 35.

a) This includes both the Black Powder lift charge and an approximation of the powder content of the shell leaders.

b) The approximate diameter reported for this asymmetric fireball was calculated for a sphere based on its approximate volume of 1100 cubic feet.

a fireball with an approximate volume of 1100 ft^3 (31 m^3) with a total duration of approximately 1.6 seconds. While there was slightly more Black Powder in the current test, that certainly cannot account for all of the difference between the two sets of results.

In the present aerial shell test, it must be considered that there was also a significant amount of non-pyrotechnic, but readily combustible, material present. For example, there was the cotton string in the black match, the paper match pipe, the plastic bags containing the lift charge, the paper making up the lift bags, the tape, and the corrugated cardboard in the carton. Thus, while these combustible materials will take essentially no part in the pyrotechnic reactions, in response to the thermal output from the pyrotechnic reactions, they will decompose to produce an amount of highly combustible gas and particulate matter. Surely these gasses and particulates will then burn as air oxygen mixes into the periphery of the fireball. This added fuel will act to sustain the duration of the fireball and allow it to further expand before cooling. Note that the combustion products from a fireball continue to expand somewhat after the fireball is considered to have ended. It is the cooling of the fireball, from the loss of heat, that marks its end. Accordingly, burning the additional non-pyrotechnic fuel must be expected to both extend the duration of the fireball and thereby increase its volume beyond that of the fireball without the additional non-pyrotechnic fuel.

In addition to the non-pyrotechnic combustibles adding to the volume and duration of the fireball, another factor must also be considered for the case of a substantial fireball produced inside the cargo area of a truck. In that case, the fireball would be expected to further increase in both its size and duration. Inside the cargo area, the pyrotechnic combustion products will displace the air, thus limiting the mixing and cooling of the fireball by incorporating cool air into it. In addition, some of the radiated thermal energy will be reflected back into the fireball from the surfaces (walls, ceiling, etc.) inside the cargo area, again acting to extend the duration of the fireball.

Using the data reported in the literature and from this test—using a case of simulated aerial shells—it would be possible to comment on the personal survivability of a collection of accident scenarios involving various amounts of aerial shells and in various circumstances. While that information is certainly an important subject, it is beyond the scope of the current article.

Acknowledgement

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