An earlier draft appeared in *Proceedings of the 3rd International Symposium on Fireworks*, 1996.

An Instrument for the Evaluation of Black Powder as a Propellant for Aerial shells

K. L. and B. J. Kosanke
PyroLabs, Inc., Whitewater, CO 81527 USA

ABSTRACT

None of the standard laboratory tests for Black Powder provide a direct indication of its performance characteristics for propelling aerial fireworks shells. Typically such testing must be performed by firing dummy projectiles on a test range—with all the problems that can entail, including the use of fairly large amounts of Black Powder for each test sample. Accordingly, a small, inexpensive laboratory test apparatus was developed, which uses only a minimal amount of powder per firing. The performance of the instrument was quantified regarding the effect of operating temperature, sensitivity of output to variations in ignition point, the effects of combustion product accumulation in the bore of the apparatus, the effect of grain size distribution, and the statistical precision of the results. Following these characterizations, the instrument was used to evaluate the performance of a series of Black Powder samples.

Introduction

There are standard tests used to determine the performance of Black Powder (e.g., strand, quickness, and flame spread tests). However, none generate results that directly indicate how the powder will perform when used as lift charge for aerial shells with their substantial clearance within their fireworks mortars. Typically, one must resort to test firing aerial shells to collect the desired information. This requires access to a test range and having to deal with problems such as weather. Accordingly, in preparation for studies[1–3] of the effects of varying materials and processing methods on the performance of Black Powder when used to fire aerial shells, a small-scale, simple, cost-effective, laboratory apparatus was constructed. This article describes the apparatus, presents data characterizing the device, and compares the performance of a few Black Powder samples. Figure 1, shows the instrument in operation, where combustion gases can be seen exiting the apparatus through a series of vents. Presumably, the sparks seen are pieces of still burning black powder exiting with the combustion gases.

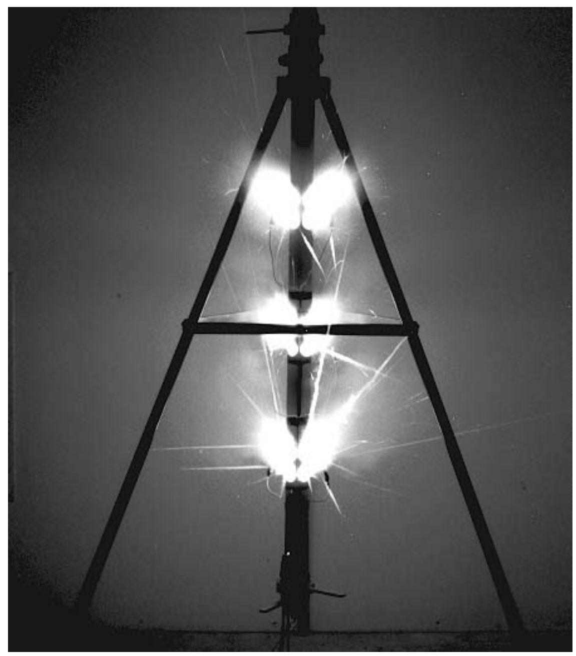

Figure 1. Test instrument shown during firing of a Black Powder test sample (time exposure).

Design and Construction

To keep cost to a minimum, whenever possible, off-the-shelf components and pre-existing hardware were used. Another important consideration was the size of the apparatus. Small size generally equates to less expensive, requiring smaller samples of powder, and being more suitable for indoor use. This apparatus was built around the use of golf balls as projectiles,[4] which are rugged (reusable) and cost less than one dollar each. With this size mortar, cylindrical projectiles could also be made using 1.75-inch (45-mm) ny-

Table 1. Specifications of Projectiles and Mortar.

Parameter, Units	Projectile Type[(a)] Spherical	Projectile Type[(a)] Cylindrical	Mortar
Diameter, inches (mm)	1.68 (43)	1.75 (44)	1.89 (48)
Cross Sectional Area, in^2 (cm^2)	2.22 (14.3)	2.41 (15.5)	2.81 (18.1)
Projectile to Mortar Area Ratio	0.79	0.86	n/a
Typical 3-in. (76-mm) Shell Area Ratio[(b)]	0.76 to 0.84	0.76 to 0.84	n/a
Weight, ounces (Mass, grams)	1.6 (46)	2.8 (78)	n/a
Density, g/cm^3	1.12	1.13	n/a
Typical 3-in. (76-mm) Shell Density	0.76[(c)]	0.75[(d)]	n/a

(a) Spherical projectiles were golf balls; cylindrical projectiles were nylon rods.

(b) These are values for 2.62- and 2.75-inch (67- and 70-mm) diameter shells, respectively, and a 3.00-inch (76-mm) mortar.

(c) Assuming a 2.75-inch (70-mm) diameter spherical projectile weighing 0.3 pound (mass of 0.14 kg).

(d) Assuming a 2.75-inch (70-mm) diameter by 2.5-inch (64-mm) long cylindrical projectile weighing 0.4 pound (0.18 kg).

lon rods, see Figure 2. The material for the mortar and barrel of the apparatus was commercial drill stem tubing, which fit the golf ball fairly well and still allowed the use of standard 2-inch (51-mm) pipe fittings. Table 1 presents some information about the projectiles, the test apparatus mortar, and typical values for aerial shells.

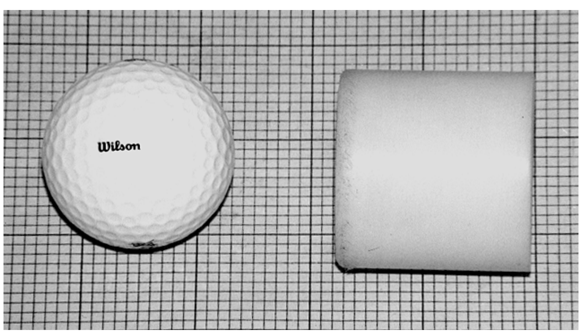

Figure 2. Typical projectiles, golf ball and short length of nylon rod, are reusable.

The fit of the projectiles in the test mortar is an important parameter for the instrument to provide meaningful results. As shown in Table 1, the fit of the golf ball and nylon rod in the mortar, as indicated by cross sectional area ratios, is in close agreement with that for small aerial shells. The density of the test projectiles, however, is higher than that of typical small aerial shells. This is not a serious problem; however, if desired, the test projectiles could be drilled and capped to lower their densities.

The instrument consists of a combination of a mortar, a time-of-flight velocity measurement section, and a projectile arrester. The apparatus and its supporting tripod are shown in Figure 3. The bottom-most portion of the vertical tube is the mortar. It is closed at the bottom with a breech plug (Figures 4 and 5) that is threaded into a standard 2-inch (51-mm) pipe union for attachment to the mortar.

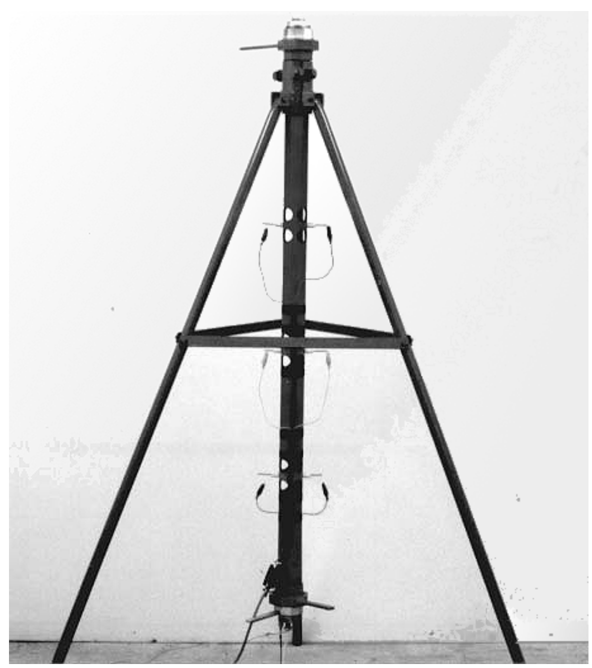

Figure 3. Black powder test instrument and tripod.

In an earlier study of aerial shell exit times[5a] the authors observed that even apparently identical aerial shells (using the same type of electric matches and firing set) typically demonstrated a wide range of mortar exit times. A likely explanation for this is that there are significant differences in the dynamics of flame spread and combustion. Among other things, this may be caused by relatively minor differences in the relative geometry of the lift powder charge, the point of ignition, and the shell position. For this reason the breech plug of this instrument was designed to provide an easily reproducible geometry for the powder, electric match and projectile (see Figure 4). Shown removed from the center of the plug in Figure 5, is the mechanism for inserting and securing an electric match. Also shown in Figure 5, on the bottom left side of the breech plug is a piezo-electric pressure sensor (PCB Piezotronics[6] 101A04). On the right side of the plug is the attachment of a thermocouple. The breech plug design has subsequently been modified to mount the thermocouple approximately 1-inch (25-mm) deep inside the plug. This reduces ambient temperature effects allowing a more accurate reading of the plug and powder temperature. Another modification was the addition of two small electric cartridge heaters inserted into the breech plug. These are used to raise and hold constant the temperature of the plug and powder.

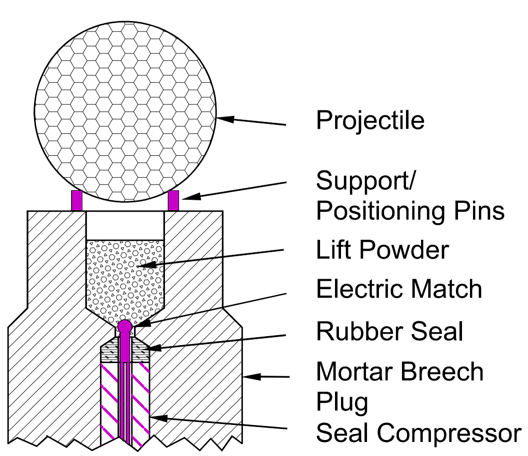

Figure 4. Cross sectional drawing of the breech plug for the mortar portion of the instrument.

Figure 6 shows one of three sets of holes in the apparatus for the escape of the combustion gases. It also shows a trip-wire for measuring the time-of-flight of the projectile. The trip-wire is a short

Figure 5. Breech plug for mortar portion of test instrument.

length of computer wirewrap that is held in place, after tensioning, with a pair of wedges inserted into 1/8-inch (3.1-mm) plastic tube fittings. Initially, graphite pencil leads were used as trip-wires; however, they sometimes failed prematurely. A series of three trip-wires spans a total distance of 2 feet (0.61 m) thus providing two one-foot (0.30 m) time-of-flight segments. Trip-wire break times are measured to 0.1 millisecond, using an existing instrument[7] that also fires the electric match.

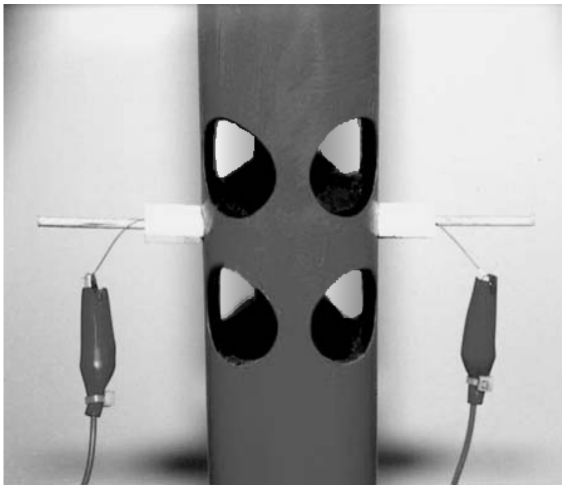

Figure 6. One set of combustion gas exhaust holes and one timing trip-wire.

Above the third set of exhaust holes and trip-wire, is the arrester portion of the instrument. This is simply a closed portion of pipe, in which a buildup of gas pressure in front of the projectile is expected to begin reducing the velocity of the projectile. However, the primary arrester is a hard rubber disk mounted in the pipe using another pipe union. This keeps the projectile within the apparatus. After impacting the arrester disk, the projectile falls relatively slowly back to the bottom of the apparatus.

The apparatus is essentially symmetrical in its design; thus it can be inverted, with the breech plug and arrester disk switched from end to end. This symmetry, and because the distance to the first exhaust holes is different on opposite ends of the pipe, makes it possible to have two different mortar lengths with a single instrument. One end provides a mortar length of approximately 5 times the diameter of the mortar, and the other, approximately 8 times its diameter. These are approximate lengths because the mortar section does not end abruptly; rather the solid mortar section ends at the round exhaust holes.

In addition to the trip-wire data (providing exit times from the mortar and muzzle velocities), the instrument also generates mortar pressure data. This data is collected using a digital storage oscilloscope, triggered by the application of power to the electric match. Figure 7 presents an example of a typical mortar pressure profile. Using such data, peak pressure (determined by visually smoothing the data) and pressure impulse (area under the curve) are easily obtained. In addition, other interesting data are available: delay time (defined as the time between applying electric current to the electric match and when mortar pressure rises to 10% of maximum), rise time (defined as the time for the pressure to rise from 10 to 90% of maximum), projectile exit time (defined as the time from match firing to the break in the pressure curve indicating the exit of the projectile), exit pressure (defined as the pressure at time of projectile exit), and impulse time (defined as the time difference between start of the pressure pulse and projectile exit).

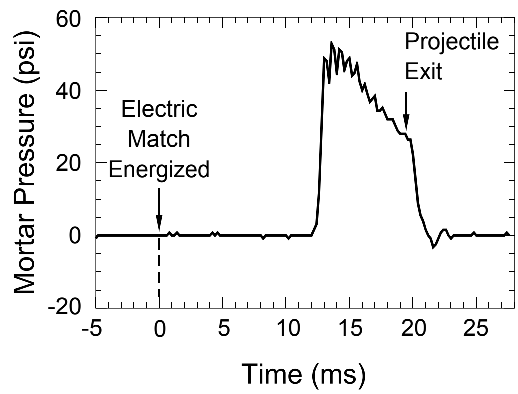

Figure 7. A typical mortar pressure profile for a golf ball (1 psi = 6.89 kPa).

Characterization of the Instrument

Many factors affect the burn rate of pyrotechnic materials (e.g., temperature and grain size). Other factors affect the efficiency of propulsion (e.g., clearance around a projectile). To the extent that any of these factors may change during or between test runs, they need to be controlled or the data corrected. Accordingly, one needs to know how these factors affect the data, such that either the necessary level of control can be determined, or the necessary correction can be applied.

Point of Ignition

After a few initial test firings, the first characterization data collected was on the effect of varying the point of ignition of the lift powder. The normal location of the electric match is at the very bottom of the powder chamber in the breech plug. Figure 8 demonstrates the reproducibility of the pressure pulse achieved for three golf ball firings using 5.0 g (0.18 oz) loads of Goex[8] 4FA powder, with the instrument at a constant temperature.

(It is interesting to note that the pressure pulse data seems to demonstrate damped ringing of a constant frequency of approximately 1.6 kHz. This same feature was seen in many pressure peaks. At the present time, the authors are not prepared to suggest an explanation.)

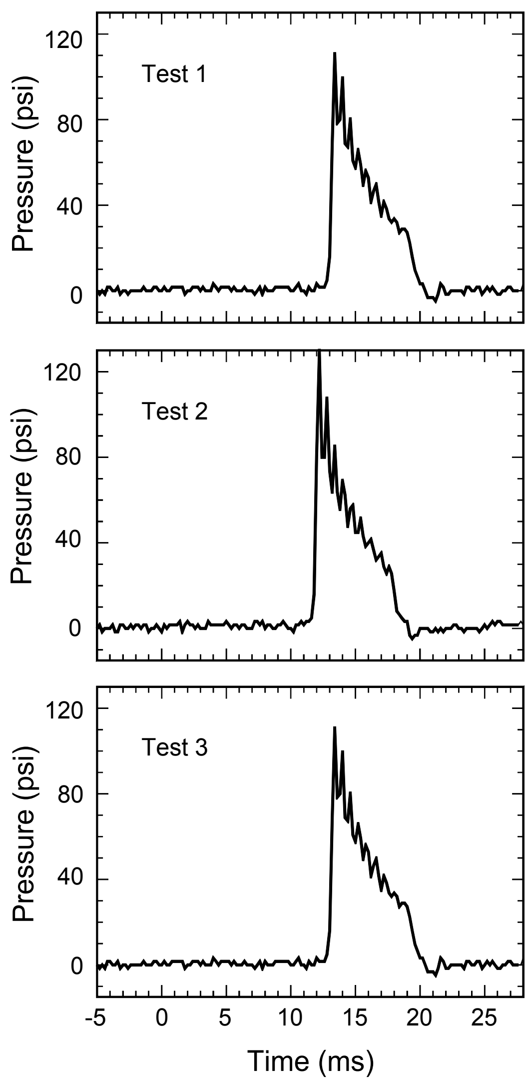

Figure 8. Illustration of reproducibility of test firings with electric match in its normal position (1 psi = 6.89 kPa.)

In addition to the data presented in Figure 8, with the electric match in its normal position, a pair of firings with the same powder load had the match raised 0.2 and 0.6 inch (5 and 15 mm) above its normal position, see Figure 9. The purpose of these firings was to help establish the degree of sensitivity of the instrument to varying electric match positions. Figure 10 and Table 2 show the results of these tests. Raising the ignition point 0.2 inch (5 mm) reduced muzzle velocity by approximately 10%; raising the ignition point 0.6 inch (15 mm) reduced muzzle velocity by approximately 50%. Obviously, closely controlling the location of the electric match is important. This observation supports the conclusion that maintaining a constant ignition point, and powder and projectile geometry are essential for consistent results. Toward this end, the operator visually verified the position of the electric match before each test reported herein; then after loading the powder, the plug was tapped several times to settle and even the powder level in the chamber.

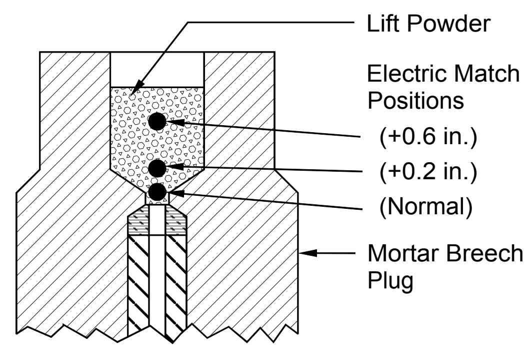

Figure 9. Illustration of electric match positions in breech plug.

Temperature

With each firing, the breech plug and mortar retain some of the thermal energy, which raises their temperature, and that of the next load of powder. This increases muzzle velocities and affects other results.[9,5b] Accordingly, to establish how elevated temperature affects results, a series of individual firings was conducted, each using 5.0 g (0.18 oz) of Goex 4FA powder, with breech plug temperatures ranging from 16 to 130 °F (–9 to 54 °C). The powder samples were conditioned to the approximate temperature of the instrument before loading. After loading the powder into the combustion chamber, the powder was allowed to thermally equilibrate for five minutes before firing. These results are presented in Table 3 and graphically in Figure 11.

Table 2. Muzzle Velocity and Pressure Data as a Function of Electric Match Position.

Match Position in.	(mm)	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time (ms)	Delay Time (ms)
0.0	(0)	200	(61)	92	(630)	6.0	12.8
		220	(67)	108	(740)	6.0	13.0
		202	(62)	96	(660)	5.9	11.1
0.2	(5)	196	(60)	48	(330)	7.3	12.5
0.6	(15)	99	(30)	12	(83)	18.4	15.2

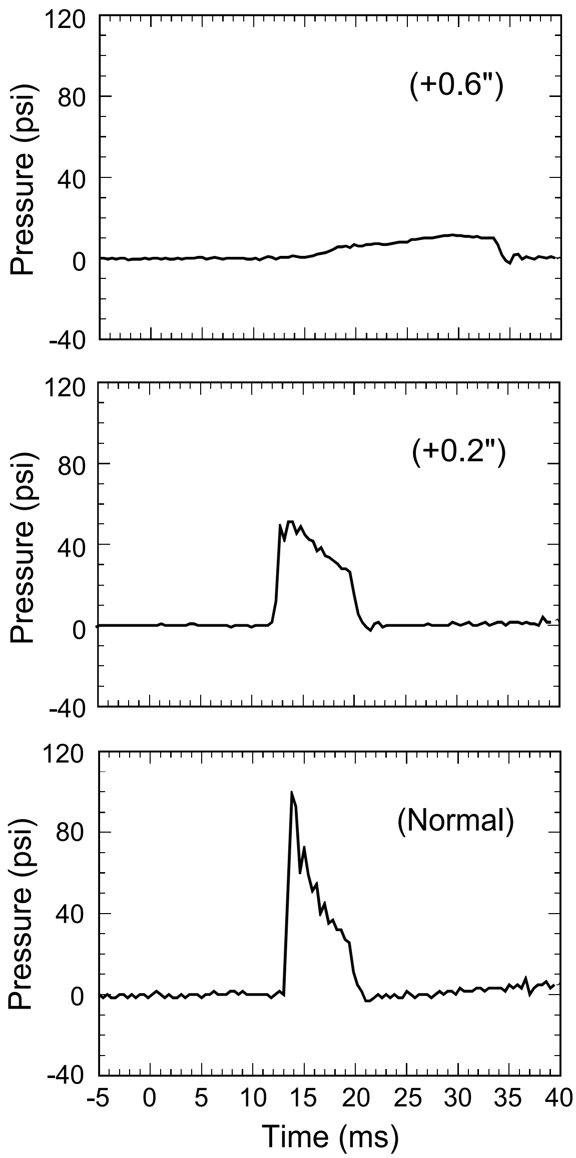

Figure 10. Typical mortar pressure profiles as a function of electric match position.

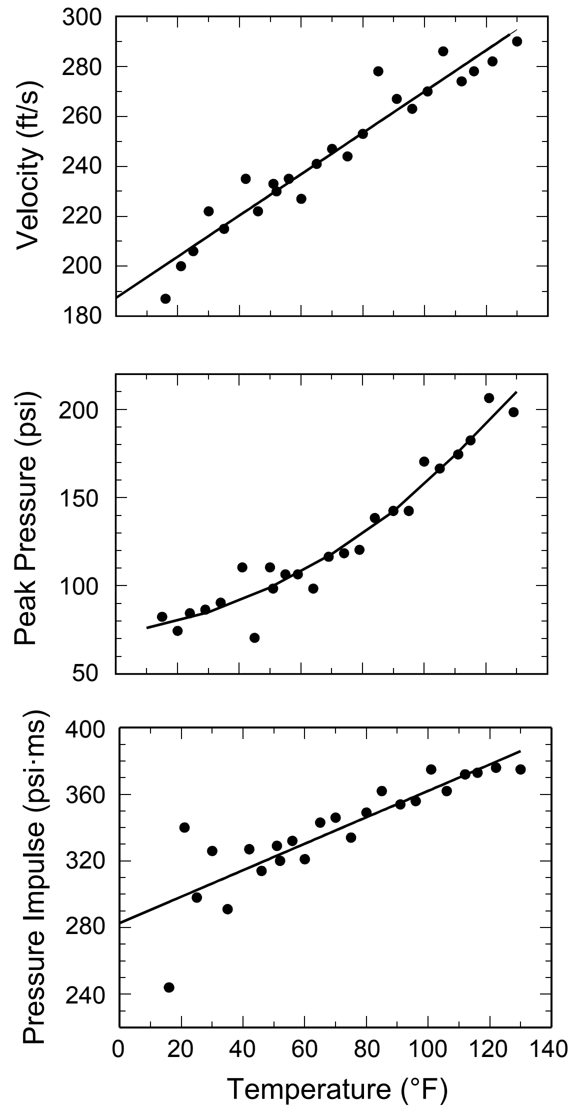

Figure 11. The effect of temperature on muzzle velocity, peak pressure, and impulse pressure.

As an alternative to running multiple tests at fewer temperatures, individual firings were run at a relatively large number of temperatures. This was done for several reasons. First, the primary

Table 3. Muzzle Velocity and Pressure Data as a Function of Temperature.

Temperature °F	(°C)	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time ms	Pressure Impulse psi · ms	(MPa · ms)	Delay Time ms
16	(–9)	187	(57)	84	(580)	6.8	244	(1.68)	12.2
21	(–6)	200	(61)	76	(520)	7.0	340	(2.34)	11.2
25	(–4)	206	(63)	86	(590)	6.9	298	(2.06)	11.2
30	(–1)	222	(68)	88	(610)	7.0	326	(2.25)	9.0
35	(2)	215	(66)	92	(630)	6.6	291	(2.01)	15.9
42	(6)	235	(72)	112	(770)	6.0	327	(2.25)	12.9
46	(8)	222	(68)	72	(500)	7.2	314	(2.16)	11.0
51	(11)	233	(71)	112	(770)	5.7	329	(2.26)	12.0
52	(11)	230	(70)	100	(690)	6.4	320	(2.20)	10.5
56	(13)	235	(72)	108	(740)	6.0	333	(2.29)	15.0
60	(16)	227	(69)	108	(740)	6.6	321	(2.21)	12.0
65	(18)	241	(74)	100	(690)	6.0	343	(2.36)	10.3
70	(21)	247	(75)	118	(810)	6.0	346	(2.39)	11.0
75	(24)	244	(74)	120	(830)	5.8	334	(2.30)	11.0
80	(27)	253	(77)	122	(840)	5.8	349	(2.41)	11.0
85	(29)	278	(85)	140	(960)	5.0	362	(2.49)	9.1
91	(33)	267	(81)	144	(990)	5.2	354	(2.44)	8.9
96	(56)	263	(80)	144	(990)	5.4	356	(2.45)	9.4
101	(38)	270	(82)	172	(1190)	5.0	375	(2.58)	10.6
106	(41)	286	(87)	168	(1160)	5.0	362	(2.49)	9.5
112	(44)	274	(84)	176	(1210)	5.2	372	(2.56)	8.8
116	(47)	278	(85)	184	(1270)	5.2	373	(2.57)	10.5
122	(50)	282	(86)	208	(1430)	5.0	376	(2.59)	8.7
130	(54)	290	(88)	200	(1380)	4.8	375	(2.58)	17.1

interest was in the overall functional relationships with temperature, which could be established using regression analysis, where relatively large individual uncertainties would not distort the results. Second, it was easier to accurately measure the temperature than it was to hold temperatures constant for a set of several tests. Third, plotting the data points from individual tests allows an easy visual comparison of statistical precision of the data relative to the magnitude of change with temperature.

Over the temperature range studied, muzzle velocity increased linearly by approximately 50%, or about 0.9 ft/s per °F (0.5 m/s per °C). Over the same temperature range, peak mortar pressure increased exponentially by more than 100%, while the corresponding impulse time decreased approximately 30%. The net result is that pressure impulse increased linearly by approximately 30%.

Following these measurements, instead of correcting individual readings for variations in temperature, because it was more expeditious, the instrument and powder were held at a constant, slightly elevated temperature. To accomplish this, two small cartridge heaters were installed in the breech plug. Unless otherwise noted all of the data reported in the rest of this article was collected with an instrument temperature of 80 °F (27 °C). Based on the observed magnitude of the changes, temperature effects and the typical level of statistical precision of the data during operation, the instrument was only held to within about 2 °F (1 °C) of the target temperature.

Cleaning

With each firing of the instrument, combustion products collect within the bore of the apparatus. This build-up acts to decrease the clearance around the projectile, which results in higher mortar pressures and greater muzzle velocities. One solution would have been to wash and dry the bore of the apparatus after each test firing. However, the time required for this would not have been practical. Another possible solution was to allow the accumulation of combustion products until a steady state was achieved, wherein each firing freed about as much combustion product as was deposited. This method was tried during the temperature characterization discussed above, and was minimally acceptable. The problem with this method is that if the instrument were cleaned, many firings would have been necessary to restore the instrument to its previous steady state condition. Another problem would occur if the instrument were used in a humid environment where the hygroscopic combustion products absorbed moisture and became partially liquefied. Accordingly, this steady state strategy was rejected.

The cleaning strategy, which achieved consistent results without taking excessive time, was to clean the bore of the instrument using a tight fitting set of wire brushes after every nine firings. (If for any reason one test firing in a series was unsuccessful, a tenth firing was allowed before cleaning the apparatus.) As part of the cleaning process, the breech plug was also washed and blown dry. Using this strategy, under the same test conditions, muzzle velocities and peak pressures for the tenth firing averaged approximately 10% higher than for the first firing. This large effect could not be ignored. One possibility was to correct each test result for its position in the sequence of firings between cleanings. However, this would require accurately determining and applying correction values for each measurement in the firing sequence. Accordingly as an alternative, the authors chose to use a firing order that essentially canceled (averaged) the mortar cleaning effect. For example, in most tests, a series of three measurements was made for each of three conditions being tested (three tests each for condition A, B, and C = nine firings). Typically the test firing order was {A, B, C, B, A, C, C, B, A}. This procedure virtually eliminates any systematic effect from accumulating combustion products within the instrument. This sampling scheme was applied to a series of nine identical test firings (data discussed below and presented in Table 7). Treating the data as three separate sets, the average deviations of the three muzzle velocities and pressure impulses from their collective means was less than 2% compared with their coefficients of variation of approximately 5%.

Particle Size

Most spherical fireworks shells and small cylindrical shells are typically fired using 4FA Black Powder; accordingly, this granulation was chosen as the standard grain size for this instrument. The US specification for 4FA powder is for no more than 3% to be +12 mesh, and no more than 12% to be –20 mesh.[10] This specification is sufficiently loose that significant variation in performance might occur because of differences in particle size distributions all well within the specification limits. For this reason, a series of tests was performed on various mesh fractions from the same can of Goex powder, where each mesh fraction would easily qualify as being 4FA. The powder was sieved, and the mesh fractions observed are reported in Table 4. The results from a series of three tests of each of the various fractions are reported in Table 5.

Table 4. Observed Mesh Fractions for Goex 4FA Black Powder.

Mesh Range[(a)]	Percent
+12	1.9
12–16	52.3
16–20	43.6
–20	2.2

(a) US Standard mesh size.

The observed muzzle velocities follow the expectation that the smaller particle size material produces the highest velocities. Similarly, the

Table 5. Test Results for Goex 4FA Black Powder (Averages from Three Tests Each).

Mesh Range[(a)]	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Pressure Impulse psi ms	(MPa ms)
16 – 20	295	(90)	183	(1260)	447	(3080)
12 – 20	278	(85)	196	(1350)	417	(2870)
12 – 16	267	(81)	186	(1280)	386	(2660)

(a) US Standard mesh size.

pressure impulse results also trend as expected, following the muzzle velocity results. Mortar pressure measurements in other portions of this study and other studies demonstrate that peak mortar pressures vary more widely than muzzle velocity and pressure impulse. Thus, while it is logical to expect that peak pressure would be greatest for the smaller particle size powder that was observed in this case. Apparently, the effect was not masked by the uncertainty in the pressure data.

This test was performed to determine the sensitivity of the data to small variations in powder particle size distribution. Note that there is an approximate 10% difference between the muzzle velocity and pressure impulse results for 12 to 16 mesh and 16 to 20 mesh. Accordingly, while grading test samples to the limits for the various commercial granulations may be satisfactory in many cases, it may not be sufficient. This is because minor variations in performance could be attributable to nothing more than slight differences in particle size distribution.

Free Flight Mode

A series of 21 test firings was performed outdoors with the projectile arrester removed; thus allowing the projectile to be propelled into the air. These tests were performed to determine "effective" (average) drag coefficients for golf balls in the velocity regime of interest for another project.[2] While interesting, those drag coefficient results will not be reported here except to note one thing. The average muzzle velocities recorded in the free flight mode were substantially higher than those for the same conditions in the captive mode, see Table 6. Presumably, this is the result of combustion gases escaping around the projectile and accumulating in the bore of the apparatus in front of the golf ball, and thus impeding its motion. Currently, this is the best explanation to be offered; however, the effect is significantly greater than might have been predicted. Accordingly, while captive mode test results with the instrument are expected to be diagnostic and self-consistent, in some cases, care may need to be exercised when quantitatively applying captive flight results to free flight situations.

While speculating on the subject of gas flow in the apparatus, another unexpected occurrence should be noted. Even though combustion gas has apparently passed the projectile and is impeding its progress, and even though the projectile has passed vent holes with a total area of more than 8 times the pipe diameter, the projectile continues to accelerate as it passes through the time-of-flight portion of the instrument. It is typical for velocities 5 to 10% higher to be recorded for the second (upper) one-foot (0.31 m) flight section. The only explanation offered is that once the propulsive gases have established their upward momentum in the mortar, they tend to continue in that direction and provide additional acceleration to the projectile. While this effect might have been expected, its magnitude is greater than would have been predicted.

Precision

A series of 9 firings under the same conditions was performed to determine the statistical precision of the results. These conditions for the test were: a 5.0-g (0.18-oz) powder charge of Goex

Table 6. Comparison of Muzzle Velocities for Free Flight and Captive Modes (Averages from Three Tests Each).

Powder Charge		Free Flight Muzzle Velocity		Captive Muzzle Velocity	
oz.	(g)	ft/s	(m/s)	ft/s	(m/s)
0.07	(2.0)	75	(23)	—	—
0.09	(2.5)	118	(36)	—	—
0.11	(3.0)	139	(42)	66	(20)
0.12	(3.5)	189	(58)	—	—
0.14	(4.0)	223	(68)	150	(46)
0.16	(4.5)	259	(79)	—	—
0.18	(5.0)	300	(91)	210	(64)
0.21	(6.0)	—	—	280	(85)
0.25	(7.0)	—	—	340	(104)

Table 7. Statistical Precision of Repeat Firings.

Firing Order	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time ms	Pressure Impulse psi·ms	(MPa·ms)	Delay Time ms
1	247	(75)	106	(730)	6.4	353	(2.43)	7.8
2	278	(85)	(a)		—	—	—	—
3	274	(84)	158	(1090)	5.2	392	(2.70)	9.4
4	278	(85)	155	(1070)	5.2	385	(2.65)	9.4
5	290	(88)	(a)		—	—	—	—
6	260	(79)	119	(820)	5.8	355	(2.44)	7.6
7	282	(86)	177	(1220)	5.2	384	(2.65)	8.4
8	299	(91)	162	(1120)	5.6	389	(2.68)	7.2
9	274	(84)	177	(1220)	5.4	391	(2.69)	8.6
Ave.	276	(84)	151	(1040)	5.5	378	(2.61)	8.3
Std. Dev.	15	(4.6)	28	(190)	0.4	17	(0.12)	0.9
Co. Var.[b]	5.4%		19%		8.1%	4.5%		10%

(a) Oscilloscope failed to trigger; no pressure data was recorded for this test.

(b) The Coefficient of Variation is the standard deviation expressed as a percent of the mean.

4FA Black Powder; a temperature of 90 °F (32 °C); the bore of the instrument had just been cleaned; and firing a standard golf ball. The results of these measurements are presented in Table 7. Because of the limited number of tests of each condition, the reported standard deviations were computed using the (*n*–1) method.

In examining the results in Table 7, considering the full set of data, it is apparent that the muzzle velocities and pressure impulses have fairly low coefficients of variation, approximately 5%. This is even without attempting to correct the data for systematic effects from accumulating of combustion products in the instrument between cleanings. Considering the data as three separate sets of three consecutive measurements, the one-sigma standard error for muzzle velocity or pressure impulse measurements is over three percent. This is perhaps already sufficiently low; however, a sampling scheme designed to reduce such systematic effects offers further improvement. Using the {A, B, C, B, A, C, C, B, A} sampling scheme discussed earlier, the sets of three measurements now have no more than approximately a 2% standard error.

Some Powder Test Results

Based on the experience with the characterization tests, a standard set of conditions and proce-

Table 8. The Effects of Various Black Powder Granulations (Averages from Three Tests Each).

Powder Type	Nominal Granulation mesh[a]	Glazing	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time ms	Delay Time ms
2FA	4 – 12	No	187	(57)	69	(480)	7.0	15
Cannon	6 – 12	Heavy[b]	149	(45)	33	(230)	9.9	18
3FA	10 – 16	Light[b]	273	(83)	149	(1030)	5.2	10
Fg	12 – 16	yes	268	(82)	142	(980)	4.9	9.7
4FA	12 – 20	unknown	278	(85)	159	(1100)	4.8	11
2Fg	16 – 30	yes	338	(103)	247	(1700)	4.2	9.0

(a) Values taken from reference 10, typically 3% may be coarser and 12% may be finer than the stated range.

(b) The relative thickness of the glazing was estimated visually.

dures was established. Unless otherwise noted: the projectile was a golf ball weighing 1.7 ounces (mass of 46 g); the powder load was 5.0 g (0.18 oz) of 16 to 20 mesh; the powder was ignited using a Daveyfire SA–2000 electric match at the bottom of the powder chamber; the temperature of the powder and instrument was 80 ± 2 °F (27 ± 1 °C); the short mortar end (5 times diameter) of the instrument was used; the apparatus was cleaned after every nine or ten firings; and a series of three measurements was made using the reported sampling scheme to average the effects of cleaning.

Muzzle velocity is easy to measure and must correlate quite well with pressure impulse, which is more difficult to calculate. Thus, pressure impulse was not determined for these tests. The observed standard deviation for peak pressure is quite a high (perhaps because of the apparent ringing or oscillations in the data, see Figure 3). Accordingly, the reported peak pressure results should only be used for approximating the range of forces being exerted on the mortar.

Granulation

A series of 18 test firings (three each for six different powder samples) was performed to examine the effect of various Black Powder granulations. All powders were commercially manufactured by Goex, Inc. These data were collected during the time when a steady state approach was being tried with respect to the accumulation of combustion products. Thus the velocities and pressures are somewhat higher than if the instrument had been cleaned more frequently, nonetheless, the sequence of firings was such that the data should be internally consistent. These data are presented in Table 8. It would have been preferred for comparison purposes that the powders had all been glazed. However, the powders tested were the only samples available in the lab at the time. Glazing presumably reduces the rate of flame spread as compared with unglazed powders. This, in turn, would be expected to reduce muzzle velocity and peak pressure. However, at this time the extent of these effects is unknown to the authors. Also there probably were some performance variations between different production lots of the Goex powders. It is implicitly assumed in reporting these test results that the intrinsic burn characteristics of the powders were all identical and that the differences observed are solely the result of

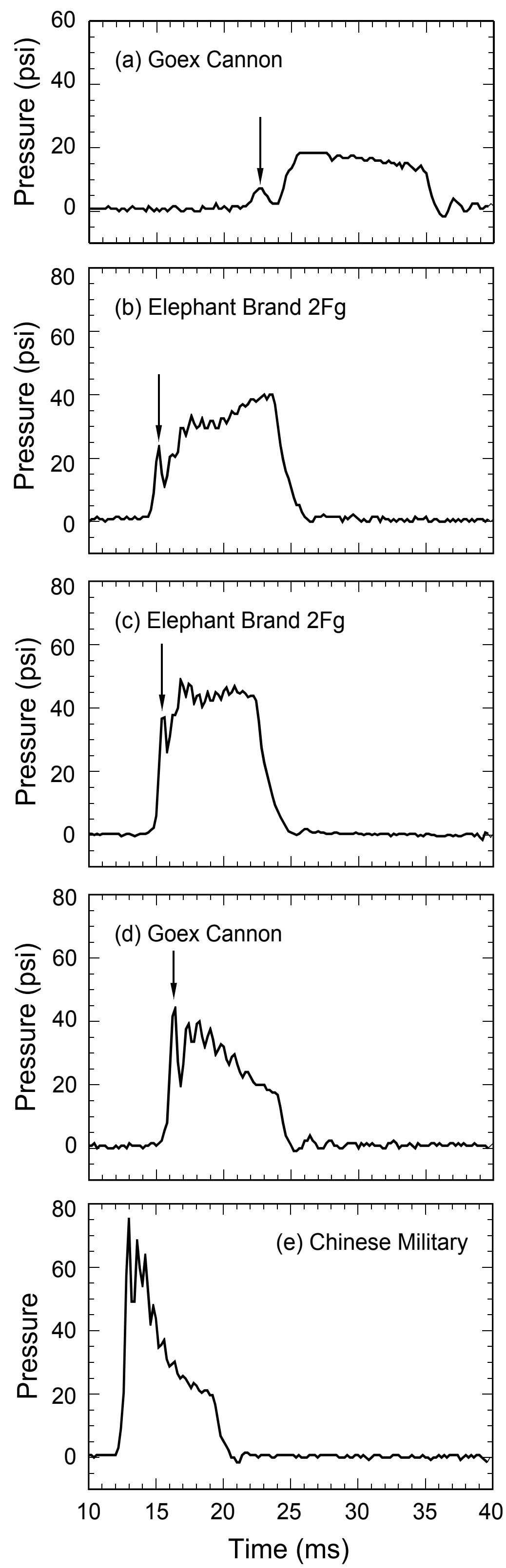

Figure 12. Examples of the precursor pressure peaks seen when firing slower burning powders.

Table 9. The Effects of Varying Black Powder Load Mass (Averages from Three Tests Each).

Lift Mass g	(oz.)	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time ms	Delay Time ms
3.0	(0.11)	66	(20)	10	(70)	19	14
4.0	(0.14)	150	(46)	32	(220)	10	14
5.0	(0.18)	210	(64)	88	(610)	6.4	12
6.0	(0.21)	280	(85)	210	(1450)	4.8	11
7.0	(0.25)	340	(104)	360	(2480)	3.2	9.4

differences in granulation. Of course, this probably was not entirely correct.

In each of the test firings of Cannon powder (and at least once for 2FA), a precursor peak was observed, such as shown in Figures 12a and 12d. [Note that time axis values in Figure 12e apply to all graphs in the series.] This was not clearly seen for any of the faster burning Goex powder samples. These precursor peaks were observed again when examining some slower burning imported powders, see Figures 12b and 12c. In examining the full series of examples in Figure 12, it appears that as the time between the precursor peak and the main impulse peak decreases, the precursor peak narrows and becomes the leading edge of the main impulse peak.

Although it seemed extremely unlikely, tests confirmed that the precursor peaks were not related to the firing of the electric match. One series of tests determined the ignition times for Daveyfire SA–2000 matches using the same firing-set as in the Black Powder tests. Firing times were found to be less than 1 ms; thus, the match firings occurred 10 to 20 ms before the precursor peaks were observed. While the presence of precursor peaks is interesting, the authors have no explanation for their existence at the present time.

Powder Charge

A series of 15 test firings was performed to examine the effect of Black Powder load mass. All powders were 4FA from Goex, Inc. These data were recorded before the electric heaters had been installed in the breech plug. The powder and instrument temperatures were 58 ± 2 °F (14 ± 1 °C). Thus, while the data are internally consistent, the velocities and pressures are lower than would have been the case for a higher temperature. From the data presented in Table 9 and Figure 13, note that muzzle velocity increases linearly with lift mass, while peak pressure increases exponentially, and impulse time decreases exponentially with lift mass.

Powder Type

A series of 30 measurements was made using Black Powder from various sources that were available in the authors' lab. These data are presented in Table 10. For comparison, values observed from roughly equivalent granulations of Goex powder are also included. Some of the pres-

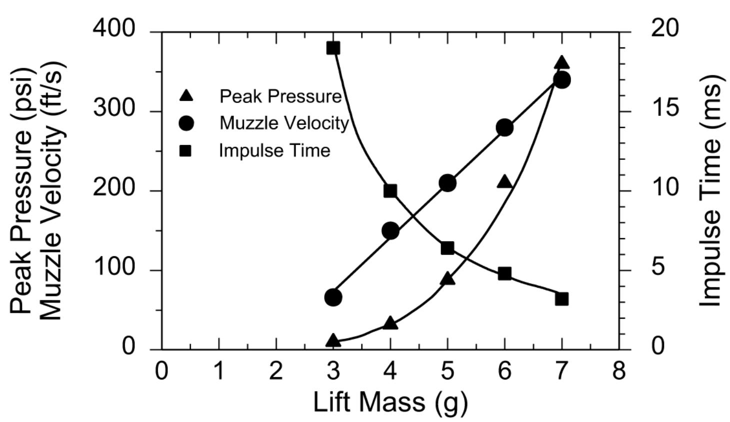

Figure 13. Graph of peak pressure, muzzle velocity and impulse time as functions of lift mass.

Table 10. Performance Values of Various Sources of Black Powder (Averages from 3 Tests Each).

Powder Source	Granulation[(a)]	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time ms	Delay Time ms
Elephant Brand	Cannon	69	(21)	11	(76)	18	30
Goex	Cannon	149	(45)	33	(230)	9.9	18
Elephant Brand	Fg	82	(25)	13	(90)	18	20
Temp. of Heaven	Fg	98	(30)	22	(150)	14	20
Chinese Military	Fg	179	(55)	63	(430)	7.6	13
Goex	Fg	268	(82)	142	(980)	4.9	9.7
Chinese Military	2Fg	172	(52)	31	(210)	9.7	15
Elephant Brand	2Fg (1996)	210	(64)	43	(300)	10	16
Elephant Brand	2Fg (1994)	247	(75)	79	(540)	6.2	11
Goex	2Fg	338	(103)	247	(1700)	4.2	9.0

(a) In the case of some of these powders, this is only an estimate based on its physical appearance.

sure pulse shapes for various brands and powder types were surprisingly different from what had been expected. See Figure 14. At this time, the authors are not prepared to suggest an explanation of the pressure pulse shapes, except to note the likely presence of precursor peaks.

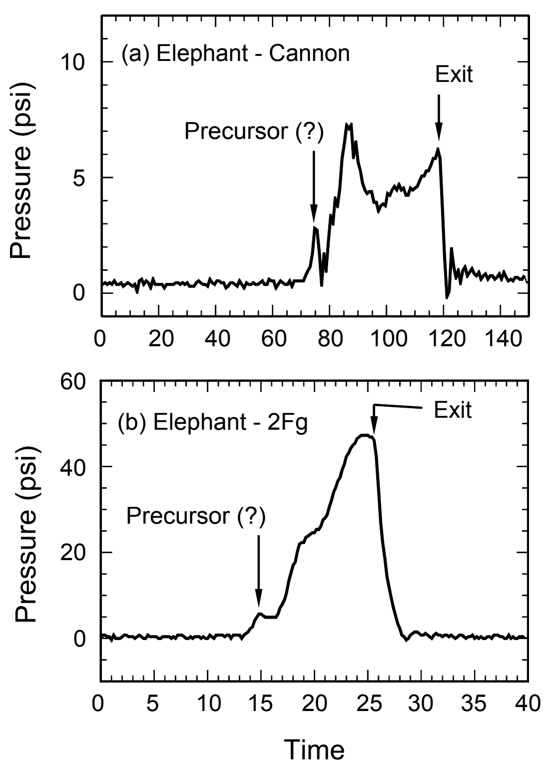

Figure 14. Examples of two unexpected pressure pulse shapes.

Conclusion

The instrument for testing Black Powder, after only minor modifications, has met its design criteria. It is small and portable; it costs approximately US$500 (not including electronics already on hand); it works reliably and requires low maintenance (cleaning); it consumes only small amounts of powder and can be fired indoors; and it uses a variety of inexpensive reusable projectiles. The significant differences in the velocities observed in the captive vs. free flight modes is disappointing, although should not interfere with the studies being undertaken using this instrument.

It is not clear whether inferences drawn from this small caliber instrument will apply directly to large caliber mortars and aerial shells. However, that was not an objective for the current instrument. Further, the success of this small-scale apparatus suggests that the design should be practical for a larger scale instrument, should that be needed.

It was not the principal purpose of this article to present Black Powder data from which significant conclusions could be drawn. Nonetheless, a few points are worth mentioning:

- The sensitivity of muzzle velocity to variations in ignition point geometry is surprisingly great. This suggests that, if preparing for a competition at the highest levels, where precise placement of shells is important, it may be worth carefully controlling the ignition and burning of the lift charge. Specifically, the ignition stimulus and geometry should be as consistent as possible, as well as the source, granulation, amount, and packaging of the lift charge.

- The muzzle velocities achieved by the Elephant brand and Chinese powders were significantly less than for the equivalent Goex granulations. This suggests that much (all?) of the potential cost advantage from using these less expensive powders may be nonexistent.
- The difference in performance between the same grades of Elephant brand powder acquired two years apart suggests greater batch-to-batch variability than might have been anticipated. (It would be interesting to know what degree of variability occurs between batches of Goex powder.)
- Aerial shells fired in winter typically do not reach the same heights as in the summer. Were it desired, the temperature data in this article might be used to determine the adjustment needed to compensate for the reduction in muzzle velocity.

Acknowledgments

The authors gratefully acknowledge the technical and editorial suggestions of W. Ofca and C. Wilson in the preparation of this paper.

The authors are also grateful to Ben Barrett of Hodgdon Powder, Coonie Coyle of Coonie's Explosives and Black Powder, and Elephant Brand Powder for supplying some powder samples used in this study.

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