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Flash Powder Output Testing: Weak Confinement

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ABSTRACT

A variety of flash powders were tested under weak confinement to determine the sound pressure levels and tonal characteristics produced. In these tests it was found that: the sound output from mixtures prepared with potassium perchlorate from four manufacturers are essentially equivalent; there are significant differences in the level of sound output as a result of using six different common aluminum powders; the addition of either of two common flow or bulking agents have essentially no effect on the sound produced; the substitution of potassium chlorate for potassium perchlorate in a common flash powder has essentially no effect on the sound produced; and the addition of antimony sulfide or sulfur reduces the duration of positive phase without increasing the level of the sound produced. In short, it was found that nothing surpassed the level of sound produced by a 70:30 mixture of reasonably high-quality potassium perchlorate and a high quality flake aluminum powder. This is significant because the use of potassium chlorate, antimony sulfide, and sulfur, can seriously increase the sensitiveness of flash powders to accidental ignition.

Keywords: flash powder, sound pressure level, blast pressure, weak confinement, positive phase

Introduction

The science of pyrotechnics as applied to fireworks frequently suffers from a lack of basic scientific data. Too often, conjecture serves as the basis for what eventually becomes "common knowledge". The sound output from flash salutes is one area in which there is much common knowledge but little quantitative data reported in the literature. This study of the sound output from a collection of flash powders under weak confinement is an attempt to provide some of the needed measurements.

For most of this study, only flash powders using 70% potassium perchlorate and 30% aluminum were examined. With these flash powders, the relative effectiveness of four types of potassium perchlorate, six types of aluminum, and two bulking agents were examined. Following this, a series of seven flash powders using one or a combination of potassium chlorate, barium nitrate, antimony trisulfide and sulfur were tested for sound output under the same conditions.

Background

All blast waves, even those produced by radically different explosives have much the same basic shape,[1a] illustrated in Figure 1. The blast wave is a shock wave, traveling greater than the speed of sound in air. Prior to the arrival of the shock front, ambient (atmospheric) pressure is unaffected. With the arrival of the shock front, there is a near instantaneous rise in pressure (overpressure) to some peak value. Thereafter, overpressure falls, returning to ambient level. This excursion is termed the "positive phase" of the blast wave. The peak overpressure attained is a function of the magnitude of the explosion and, to a lesser extent, on ambient pressure. Except for distances very close to the explosive, there is a "negative phase" of the blast wave.[1b] This negative phase is much less extreme than the positive phase, although it lasts somewhat longer. Figure 2 is the blast wave recorded for one test salute used in this

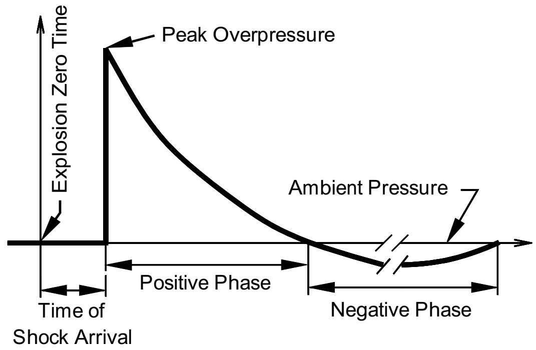

Figure 1. Sketch of a typical blast overpressure wave showing pressure as a function of time.

study. At increasing distances from the explosion, the peak overpressure becomes less, and the duration of the positive phase becomes longer; this effect is illustrated in Figure 3.

For the most part, it is only peak overpressure and the duration of the positive phase that are needed to characterize a blast wave. In terms of the sound produced, peak overpressure determines the loudness of an explosion, and the duration of positive phase presumably determines its tonal quality. That is to say the higher the overpressure, the louder the sound of the explosion. Also a short positive phase is expected to correspond to an explosion with a sharp crack sound, and a long positive phase, to a more mellow boom. Thus, from what is seen in Figure 3, all explosions sound louder and sharper at close range, and become softer and more mellow at greater distances. (For a more complete discussion of the sound levels and their measurement, see reference 2.)

Experimental Method[a]

The flash powders for these tests were each prepared by pre-screening the ingredients, rough mixing until there was uniformity in color, then tumbling at a rate of approximately 60 revolutions per minute in closed containers for one hour. This degree of mixing far exceeds that generally employed by the fireworks industry, but was chosen to eliminate any inconsistencies in test results that are caused by incomplete mixing.

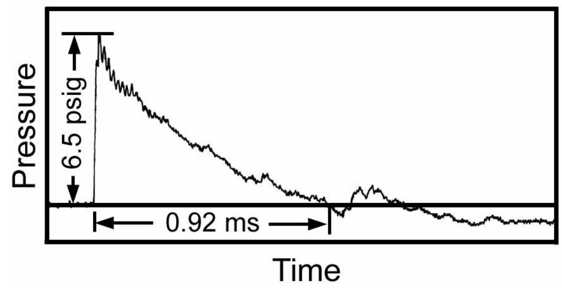

Figure 2. Blast wave from a test salute using 70:30 potassium perchlorate and German dark aluminum.

For each flash powder type, three test salutes were prepared and fired. The test salutes were made using 3 ounce (90 mL) polyethylene bottles with metal screw caps. The containers were chosen to provide an easily reproducible configuration with fairly consistent confinement. Each container was loaded with 50 g (1.8 ounce) of flash powder. A Daveyfire[3] hooded electric match (SA–2001) was used for ignition. The match was installed in the cap of each container using a thermal setting adhesive, see Figure 4. Each test salute container was mounted cap-side down, such that flash powder filled the space between the electric match and its hood. This was done to provide a minor degree of con-

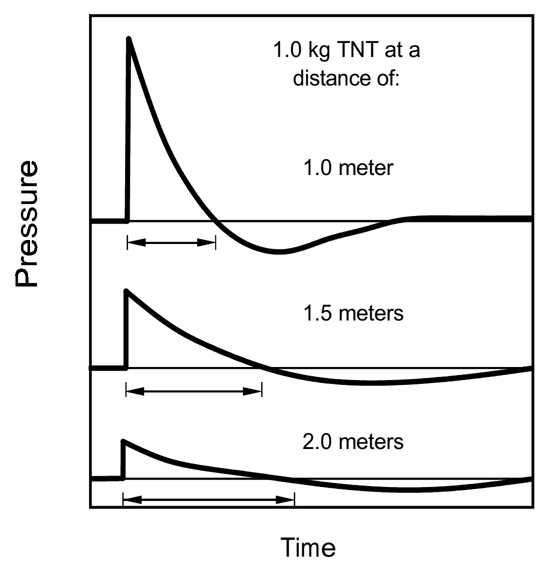

Figure 3. Sketch of the decay of a typical blast wave with distance from the explosion; based on data from Kinney & Graham.[1c]

Figure 4. An electric match installed in the cap of a test salute casing (polyethylene bottle).

finement for that small amount of flash powder, thus perhaps providing a more powerful ignition stimulus. It was anticipated that this would tend to compensate for the relatively weak confinement provided by the polyethylene bottle.

For test firing, the salutes were suspended 3.5 feet (1.2 m) above the ground. A pair of free-field blast gauges (PCB Piezotronics[4] 137A11) were positioned in line at the same height and at a distance of 4.0 feet (1.9 m) from the center of the test salute, see Figure 5. Upon firing the salute, blast overpressure data was collected using amplifying power supplies and a digital oscilloscope (50 MHz), for subsequent plotting, see Figure 6.

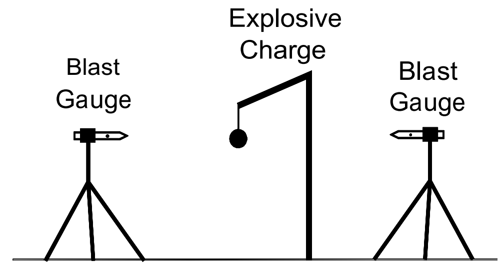

Figure 5. Sketch of the physical arrangement of test salute and blast gauges.

Test Results

In this section, the characteristics of the flash powders and the raw output data are presented. Discussion of the results is deferred to a later section.

Potassium Perchlorate Types

The four types of potassium perchlorate used in this study are described in Table 1.

As determined by microscopic analysis, only the Swedish material has fairly sharp angular particles, such as might be expected from grinding. The other three materials have particles with a more generally rounded appearance, such as might be expected from milling. The screen analysis for these materials is presented in Table 2. Small samples of potassium perchlorate, as received from the supplier, were sieved for three minutes using a vibrating sieve shaker. It is likely that the material contained some moisture and that drying may have produced slightly different sieve analyses. This not with-

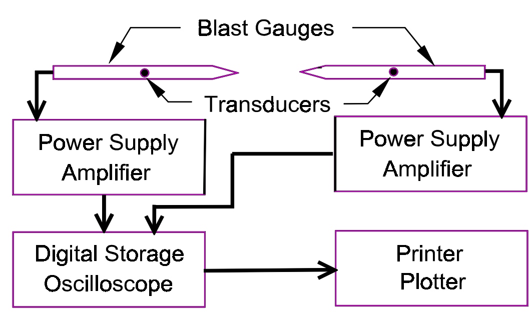

Figure 6. Block drawing for the data collection of blast overpressure data.

Table 1. Types of Potassium Perchlorate Investigated.

Source	Manufacturer	Product Information
Swedish	EKA Nobel[a]	S140, –140 mesh
US	Western Electro Chemical[5]	60 micron
Chinese	Senochem[a]	Hunan China[b]
Italian	Societa Electro-chimico[a]	Borgo Franco[b]

(a) Supplied by Service Chemical, USA.[6]

(b) No other product information available.

standing, the samples were not dried for use in the flash powders because it was believed that their condition, as received, is more typical of how they are used in manufacturing fireworks.

The flash powders used for comparison of the potassium perchlorate types were all 70:30 ratios with Obron[7] 5413 (commonly called German dark aluminum). The results from the four sets of sound pressure output tests are presented in Table 3. The data from the two blast gauges were always very nearly the same, and have been averaged for presentation in the Table.

Aluminum Types

The six types of aluminum used in this study are described in Table 4. In addition to these six aluminum powder types, a mixture of 67% (by weight) Reynolds 400 and 33% Alcan 2000 was also investigated. This was done because it had previously been suggested that a mixture of atomized and flake aluminum provided additional reactivity over either type aluminum alone.[12]

Table 2. Sieve Analysis of the Types of Potassium Perchlorate.

Source	Mesh Fraction (%)			
	+100	100–200	200–400	–400
Swedish	0.0	51.1	39.5	9.4
US	0.3	47.2	44.2	8.3
Chinese	0.1	32.3	50.7	16.9
Italian	0.0	3.0	73.0	23.9

Table 3. Sound Pressure Output for Potassium Perchlorate Types.

Potassium Perchlorate	Peak Over-Pressure (psi)	Positive Phase (ms)
Swedish	6.08	0.82
	6.16	1.00
	6.30	1.10
US	5.90	0.90
	6.20	0.95
	6.44	1.01
Chinese	5.69	0.90
	5.98	1.08
	6.02	1.15
Italian	6.21	0.90
	6.32	0.88
	6.24	0.88

For conversion to SI units, 1 psi = 6.89 kPa.

Table 4. Aluminum Powder Types.

Manufacturer	Product No.	Description[a] *[Morphology]*[b]
Obron	5413	German Dark *[Flake 8μ[c]]*
Obron	10890	American Dark *[Flake 15μ[c]]*
Alcan[9]	7100	American Dark *[Flake 13μ]*
Reynolds[10]	400	Atomized *[Spheroidal 6μ]*
US Aluminum[11]	809	American Dark *[Flake 30μ[c]]*
Alcan	2000	Bright *[Flake 36μ]*

(a) The descriptions German Dark, American Dark and Bright are used in the context generally adopted and understood by the American pyrotechnics industry. For more information on aluminum metal powder types, see reference 8.

(b) Basic particle shape and average particle size in microns. Note that 1 micron (μ) = 10^{-6} meter = 3.9×10^{-5} inch.

(c) Average particle size was estimated by the authors using microscopy.

The flash powders were all made with 70:30 ratios using Swedish potassium perchlorate and the various aluminums. The sound output data from the seven sets of tests are presented in Table 5. The data from each of the two blast gauges were always very nearly the same and have been averaged for presentation in the Table.

Flow and Bulking Agents

The two flow and bulking agents used in this study were Cab-O-Sil[13] (M-5, colloidal silica) and red wheat bran. In the first tests, flash powders were based on 70:30 mixtures of Swedish potassium perchlorate and Obron 5413 aluminum. In one test, three percent Cab-O-Sil was added to the base flash powder. In a second test, ten-percent red wheat bran was added. Another 70:30 flash powder was made using US Aluminum 809; to this base, ten-percent red wheat bran was added. In all tests, the net amount of flash powder, not including the flow or bulking agent, was 50 grams. These results are presented in Table 6.

Table 5. Sound Output Results for Aluminum Types.

Type of Aluminum	Peak Over-Pressure (psi)	Positive Phase(ms)
Obron 5413	6.08	0.82
	6.16	1.00
	6.30	1.10
Obron 10890	5.76	1.00
	6.11	0.96
	5.47	1.03
Alcan 7100	5.61	1.02
	5.61	1.08
	5.12	0.86
Reynolds 400	2.58	1.25(a)
	2.58	1.62(a)
	3.22	1.19(a)
US Aluminum 809	2.30	0.98
	2.54	1.15
	2.72	0.88
Alcan 2000	1.28	1.00
	1.52	1.12
	1.58	0.90
Reynolds 400 + Alcan 2000	2.28	1.15(b)
	2.80	1.18(b)
	1.83	1.07(b)

For conversion to SI units, 1 psi = 6.89 kPa.

(a) In each case, the Reynolds 400 flash powder produced a double blast wave, as shown in Figure 7, resulting in a longer positive phase.

(b) In each case, the use of the Reynolds 400 and Alcan 2000 mixture produced flash powder that also exhibited a weak double blast wave structure.

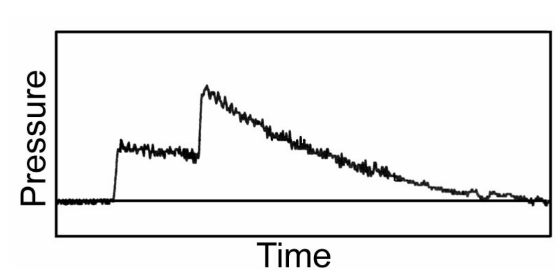

Figure 7. Typical double peaking blast wave recorded for flash powders made using Reynolds 400 aluminum.

Table 6. Sound Output Results Using Flow or Bulking Agents.

Aluminum Type *[Additive]*	Peak Over-Pressure (psi)	Positive Phase (ms)
Obron 5413 *[None]*	6.08	0.82
	6.16	1.00
	6.30	1.10
Obron 5413 *[3% Cab-O-Sil]*	6.32	0.98
	6.18	0.85
	6.12	0.93
Obron 5413 *[10% Red Bran]*	5.61	0.93
	6.36	1.05
	6.02	0.90
US Alum. 809 *[None]*	2.30	0.98
	2.54	1.15
	2.72	0.88
US Alum. 809 *[10% Red Bran]*	1.73	1.00
	1.92	0.95
	2.12	1.05

For conversion to SI units, 1 psi = 6.89 kPa.

Formulations

Many different flash powders are used in fireworks. However, only seven flash powder formulations were used in this study. They are listed in Table 7, along with literature references. These formulations were chosen to provide information on the effect of the choice of oxidizer and the use of sulfur and antimony sulfide. However, beyond that criterion, the choice was somewhat arbitrary. Table 8 lists the sound output results from the test salutes using these formulations.

Discussion of Results

It is important to note that the results and conclusions reported in this article are only valid within the context of this study. For example, only three tests were conducted for each flash powder; the average variation about the mean peak overpressures was about 4% and the average deviation in the duration of positive phase was about 6%. Accordingly, any small differences reported for these parameters may be merely statistical in origin. Further, these results are only valid for the conditions examined, specifically, weak confinement with a moderately powerful ignition stimulus.

Table 7. Flash Powder Formulations Used in Test Salutes.

	Flash Formulations (weight percent)						
Ingredient	1	2	3	4	5	6	7
Potassium perchlorate ($KClO_4$)	70	64	62	70	—	—	—
Potassium chlorate ($KClO_3$)	—	—	—	—	70	64	—
Barium nitrate ($BaNO_3$)	—	—	—	—	—	—	68
Aluminum, Obron 5413 (G.D.)	30	—	—	—	—	—	—
Aluminum, Obron 10890 (A.D.)	—	27	23	30	30	9	—
Aluminum, Alcan 2000 (Bright)	—	—	—	—	—	—	23
Antimony trisulfide (Sb_2S_3)	—	—	15	—	—	9	—
Sulfur (S)	—	9	—	—	—	18	9
Reference	(a)	14	14	(a)	(a)	15	16

(a) This is a common formulation with no specific reference.

Table 8. Sound Output Results for Test Formulations. (Also, see Table 7.)

Formulation No. and Description	Peak Over-Pressure (psi)	Positive Phase (ms)
1) $KClO_4$ + G.D.	6.08	0.82
	6.16	1.00
	6.30	1.10
2) $KClO_4$ + A.D. + S	5.90	0.82
	5.88	0.92
	5.76	0.88
3) $KClO_4$ + A.D. + Sb_2S_3	5.85	0.78
	5.90	0.92
	5.75	0.84
4) $KClO_4$ + A.D.	5.76	1.00
	6.11	0.98
	5.47	1.03
5) $KClO_3$ + A.D.	6.31	0.88
	5.94	1.15
	5.10	0.78
6) $KClO_3$ + A.D. + S + Sb_2S_3	3.50	0.72
	3.77	0.78
	3.64	0.63
7) $BaNO_3$ + Bright + S	0.22	1.00
	0.17	1.20
	0.11	1.00

For conversion to SI units, 1 psi = 6.89 kPa.

Table 9 presents the averages of the sound output data from the tests using potassium perchlorate from different sources. Also in the table are sound pressure levels in dB and relative loudness (*N*). Decibel and loudness values were calculated using the following equations:[17]

$$\text{dB} = 170.8 + 20 \log P \quad (1)$$

$$\log N = 0.03 \text{ dB} - 1.2 \quad (2)$$

where P is peak overpressure in psi.

It must be noted that the reported dB levels were calculated using peak overpressures measured with an instrument with an extremely fast rise time. Thus, these values will be somewhat greater than would have been found using conventional sound measuring equipment, even when using their peak-linear mode setting. (For a more complete discussion of sound pressure levels, loudness, and the effect of instrument parameters, see reference 18.) While it is possible that the peak overpressures observed for the Chinese potassium perchlorate are slightly less than for the other materials, it is within the limits of statistical precision of these measurements. Furthermore, it is doubtful that a typical observer would be able to detect such a small loudness difference, even if it were real. Similar comments are appropriate for the slightly larger value for the Italian potassium perchlorate.

Those materials with roundish particle shape (US, Chinese and Italian), rather than sharp angular particles (Swedish), are likely to mix more thoroughly when using procedures typical of fireworks manufacturing. Accordingly, under more typical mixing conditions than used in this study, it is possible these materials would produce slightly louder flash powder salutes.

Table 9. Average Results from Different Potassium Perchlorates.

Potassium Perchlorate Type	Positive Phase (ms)	Peak Overpressure (psi)	Sound Pressure Level (dB)	Relative Loudness
Swedish	1.01	6.18	186.5	≡1.00
US	0.95	6.18	186.6	1.00
Chinese	1.04	5.90	186.2	0.97
Italian	0.89	6.26	186.7	1.01

For conversion to SI units, 1 psi = 6.89 kPa.

Table 10. Average Results from Different Aluminums.

Aluminum Types	Positive Phase (ms)	Peak Overpressure (psi)	Sound Pressure Level (dB)	Relative Loudness
Obron 5413	1.01	6.18	186.6	≡1.00
Obron 10890	1.00	5.78	186.0	0.96
Alcan 7100	0.99	5.45	185.5	0.93
Reynolds 400	1.35[(a)]	2.79	179.7	0.62
US Aluminum 809	1.00	2.52	178.9	0.59
R. 400 + A. 2000	1.13[(a)]	2.30	178.0	0.54
Alcan 2000	1.01	1.46	174.1	0.42

For conversion to SI Units, 1 psi = 6.89 kPa.

(a) The Reynolds 400 aluminum produced double explosions, see Figure 7.

Differences in particle size and shape can play a role in determining burn rate, which in turn would influence the sound levels produced by salutes. However, generally it is the size and shape of the fuel that is of primary importance. Typically, this is because the melting point of the oxidizer is lower than the ignition temperature of the mixture. (See reference 19 for a more complete discussion of the factors affecting burn rate.) Based on the above results, for those potassium perchlorate samples examined, it seems that oxidizer particle size and shape only play a minor role in the sound levels produced.

The average durations of positive phase are also essentially within the limits of statistical precision of the measurements. Accordingly, a significant difference in the tonal quality of the sounds produced by the test salutes would not be expected, except possibly for the Italian material that may produce a slightly sharper sound.

Table 10 presents the average sound output data from the tests using different aluminum powders. For the test salutes used in this study, the sound outputs fall roughly into three groups. The first group consists of the two Obron products and Alcan 7100; these produced the greatest output, with the Alcan material possibly producing slightly lower sound levels. The Reynolds, US Aluminum, and mixture of flake and atomized aluminums produced significantly lower sound levels. The Alcan 2000 produced the least sound output.

In all cases, except when Reynolds 400 was used, the durations of positive phase were equivalent. Accordingly, it would be expected that the tonal quality of all the test salutes would be the same. With the Reynolds 400, there was some degree of double peaking of the blast wave (see Figure 7). The authors do not have a satisfactory explanation for this; however, it has never been observed in any other tests and is always observed for Reynolds 400. Thus, it seems that it must be a manifestation of the aluminum powder and not an artifact of the measurement. (It has been suggested that the second peak may be a result of a secondary aluminum dust explosion following the rupture of the test salute casing.) For whatever reason the double peak is produced, it would seem that this aluminum would produce a more mellow sound than the others.

Table 11 presents the average sound output data from the tests of flash powders with a flow or bulking agent. Recall that in all cases, the net amount of flash powder was 50 g (1.8 ounce), exclusive of the added flow or bulking agent. With the 70:30 Swedish potassium perchlorate and Obron 5413 aluminum flash powder, the agents had essentially no effect on relative loudness. However, for the flash powder using US Aluminum 809, there was a minor, but noticeable, reduction in relative loudness. It is unlikely there was a significant affect on the duration of positive phase (tonal quality). The addition of flow and bulking agents is expected to facilitate mixing and help keep flash powders from compacting over time. Thus, it is possible

Table 11. Average Results from Flow or Bulking Agent.

Aluminum Type	Flow / Bulking Agent Type	Positive Phase (ms)	Peak Over-Pressure (psi)	Sound Pressure Level (dB)	Relative Loudness
Obron 5413	None	1.01	6.18	186.6	≡1.00
	Cab-O-Sil (3%)	0.92	6.21	186.6	1.00
	Red Bran (10%)	0.96	6.00	186.4	0.98
US Aluminum 809	None	1.00	2.52	179.1	≡1.00
	Red Bran (10%)	1.00	1.92	176.5	0.85

For conversion to SI units, 1 psi = 6.89 kPa.

that their addition would produce greater relative sound output under other conditions than in this study

Table 12 presents the average sound output from the seven flash powder formulations listed in Table 7. In terms of loudness, no formulation out performed the Obron 5413 (German dark aluminum) and potassium perchlorate.

Of the formulations using Obron 10890 (sometimes referred to as American dark aluminum), the addition of sulfur or antimony sulfide, or the substitution of potassium chlorate for potassium perchlorate (formulations 2, 3 and 5) made no difference in loudness. However, there was a shortening of the positive phase duration with the addition of either sulfur or antimony sulfide, which should produce a sound perceived as being less mellow. That the addition of antimony sulfide produced a more brisant explosion was expected, based on common knowledge in the fireworks trade. However, it was not expected that the addition of sulfur would have the same effect. Common experience is that sulfur produces a more mellow sound. At the present, the authors have no satisfactory explanation for this. However, work is continuing to study this. Use of antimony sulfide or sulfur decreased the duration of the positive phase without increasing peak overpressure. This combination of effects means that the pressure impulse produced is less for these flash powders. In turn, that may mean that the blast effect perceived by the audience, the so-called "chest thump", will be less for salutes using these flash powders.

When both sulfur and antimony sulfide were added and potassium chlorate was used as the oxidizer (formulation 6), the duration of positive phase was reduced further. However, there

Table 12. Average Results from Various Formulations.

Formulation Number and Description	Positive Phase (ms)	Peak Over-Pressure (psi)	Sound Pressure Level (dB)	Relative Loudness
1) $KClO_4$ + Obron 5413	1.01	6.18	187.6	≡1.00
2) $KClO_4$ + Obron 10890 + S	0.87	5.85	186.1	0.97
3) $KClO_4$ + Obron 10890 + Sb_2S_3	0.85	5.83	186.0	0.96
4) $KClO_4$ + Obron 10890	1.00	5.78	186.0	0.96
5) $KClO_3$ + Obron 10890	0.94	5.78	186.0	0.96
6) $KClO_3$ + Obron 10890 + S + Sb_2S_3	0.71	3.64	182.0	0.73
7) $BaNO_3$ + Alcan 2000 + S	1.07	0.17	155.4	0.11

For conversion to SI units, 1 psi = 6.89 kPa.

was also a significant reduction in loudness of the test salutes (presumably a result of its rather low percentage of aluminum). The use of potassium chlorate, sulfur or antimony sulfide in flash powders can increase the sensitiveness to accidental ignition from one or more factors: impact, friction, electrostatic discharge or temperature.[20] The use of a combination of potassium chlorate and sulfur or antimony sulfide is expected to result in a substantial increase in sensitiveness. While a discussion of these effects would be interesting and important, they are beyond the scope of this article.

Under these test conditions, the test salutes made using formulation 7, with barium nitrate and Alcan 2000 (bright) aluminum, resulted in reports of considerably reduced loudness, but with a positive phase duration perhaps a little longer than typical of the other flash powders.

Conclusion

There are a number of inferences that can be drawn from the above data sets; however, these must only be made within the context of these measurements. It is possible that other conclusions would be reached for other experimental conditions. Nonetheless, these data imply:

- The sound output from mixtures prepared with common sources of potassium perchlorate from four manufacturers is essentially equivalent.
- There are significant differences in the level of sound output as a result of using six different common aluminum powders.
- The addition of either of two common flow or bulking agents have essentially no effect on the sound produced (for freshly prepared items).
- The substitution of potassium chlorate for potassium perchlorate in a common flash powder has essentially no effect on the sound produced.
- The addition of antimony sulfide or sulfur reduces the duration of positive phase without increasing the level of the sound produced.

In short, nothing surpassed the level of sound produced by a 70:30 mixture of reasonably high-quality potassium perchlorate and a high quality flake aluminum powder. This is significant because the use of potassium chlorate, antimony sulfide, and sulfur can seriously increase the sensitiveness of flash powders to accidental ignition.

It had been anticipated that, as a follow-on to this study, there would be a study of the sensitiveness of these flash powders. This was posed on the assumption that there was a performance benefit to the use of potassium chlorate and antimony sulfide or sulfur. It was thought that information would allow manufacturers to decide whether the performance gain was worth the added risk of using such formulations. However, since there is no performance advantage, there is no potential benefit and no reason to use formulations that are more hazardous. Accordingly, there is little point in measuring the sensitiveness of those formulations, and plans for that study have been abandoned.

Acknowledgments

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Note

[a] In this article, for accuracy of reporting, the actual units of measurement are given first, followed by either their SI or English equivalent.

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