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Articles accepted for publication in the *Journal of Pyrotechnics* can be on any technical subject in pyrotechnics. However, a strong preference will be given to articles reporting on research (conducted by professionals or serious individual experimenters) and to review articles (either at an advanced or tutorial level). Both long and short articles will be gladly accepted. Also, responsible letters commenting on past Journal articles will be published, along with responses by the authors.

Model Rocket Motors, Theory and Design[1]

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ABSTRACT

A semi-empirical theory is presented for the design of model rocket motors that use Black Powder for fuel. By choosing the values of a few adjustable parameters, a hobbyist can construct motors that perform satisfactorily without extensive or dangerous trial and error. Formulas are given for calculating the nozzle diameter, the combustion chamber height, and such performance descriptors as specific impulse and average thrust for any size of model rocket motor.

Keywords: model rocketry, Black Powder, rocket propulsion theory

Introduction

For a beginner, building model rocket motors without any technical knowledge is a hazardous pursuit. Because of this, the competition rules of the international model rocket association, Federation Aeronautique Internationale (FAI), prohibit the use of any motors that do not meet certified safety standards. Usually, the only motors that qualify are commercial ones. And even they can be dangerous if they are modified by the modeller or they are not used according to the manufacturer's instructions. Experimental model rocket motors of any kind introduce considerably higher risks. And those that are constructed only "by the seat of one's pants" are disasters waiting to happen. In order to use factory-made or hand-made motors with maximum safety, one must thoroughly understand and conscientiously apply the principles of rocket propulsion.

Theory

We will develop a semi-empirical theory[2] for the most common form of model rocket motor, namely one in which a solid fuel is compressed or molded into a cylindrical casing. Although the theory is quite general and applies to any cylindrically-shaped solid fuel, we will cite the adjustable parameters in ranges that pertain to Black Powder only.

The theory centers around two unitless parameters, f_{max} and f_{min}, which effectively tailor the internal geometry of the rocket motor to the power of the particular fuel. Or, alternatively, they specify what strength of fuel should be used for a fixed internal shape. The first parameter f_{max} is the ratio of the maximum burning area to the nozzle area. It can be as low as 44 for high-power, military-quality Black Powder, or it can be as high as 100 or more for haphazardly-mixed, hand-made meal. The other parameter, f_{min} compares the area of minimum burning to the area of the nozzle. It ranges from 18 to 50.

The two numbers can be optimized with extensive testing, but in practice, they usually lead to acceptable rocket performance if they each can be determined within ±10 of their ideal values. And this can be accomplished with only a few test motors. One either chooses values for several f_{max} and f_{min} pairs based on an estimate of the fuel's power, then makes prototype motors corresponding to each pair to see which works best. Or, for an existing set of rocket-

making tools, one adjusts the fuel mixture to get f_{max} and f_{min} values which match the tools' geometry. Either way, an amateur rocket builder can design reliable motors with a minimum of trial and error.

Combustion Intervals

The performance of a motor over time can be divided into two intervals: (1) the *lift-off* interval, where the motor develops the necessary surge of thrust to get itself and its payload off the ground, and (2) the *end-burning* interval, where the motor maintains its upward movement with a steady thrust. The effects of these two intervals can be visualized in Figure 1 where the thrust of this type of model rocket motor is plotted against time.

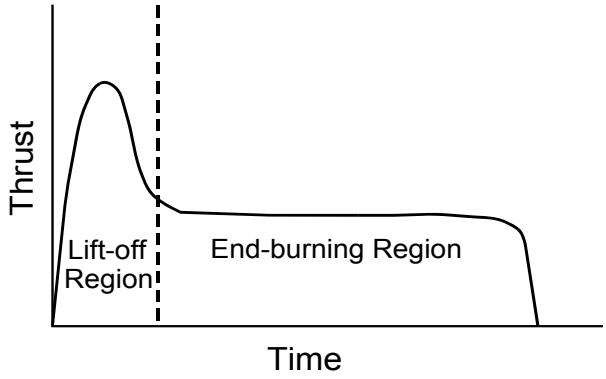

Figure 1. Combustion intervals for a solid-fuel rocket motor with a hollow combustion cavity.

The Lift-Off Region

The amount of thrust that a burning fuel can supply is directly proportional to the surface area of combustion. If a rocket motor is fueled with nothing more than a solid cylindrical mass of Black Powder, it only has the circular cross-sectional area of the cylinder as its burning surface. And an area that small is often insufficient to provide the requisite lift-off thrust. Thus, a hollow cavity of some shape is usually made in the fuel cartridge in order to increase the initial surface area of combustion.

Ignition causes burning over this larger cavity surface. As the combustion progresses, fuel is consumed. Consequently, the size of the cavity becomes larger still, and the burning surface grows. Greater volumes of gas are forced through the nozzle, and the rocket is propelled upward by ever-increasing forces. At some point, however, the burning surface becomes as large as it possibly can. This is the point that defines f_{max}, the ratio of the maximum combustion area A_{max} and the nozzle area A_{noz}:

$$f_{max} = \frac{A_{max}}{A_{noz}} \tag{1}$$

Cylindrical Cavity

Consider the case where the rocket motor has a cylindrical combustion cavity. Let the motor have an inside diameter d, a cavity height h_{cyl}, and a nozzle diameter n (Figure 2). On ignition, the fuel begins to burn away from the

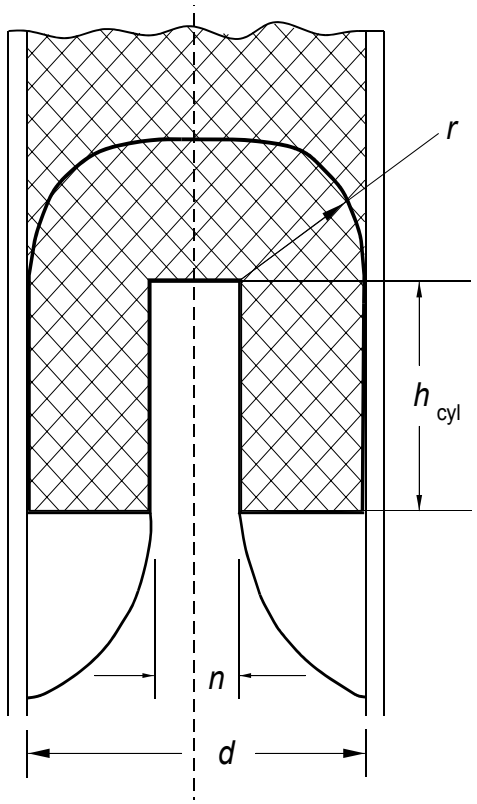

Figure 2. Cross section of a rocket motor with a cylindrical combustion cavity.

cavity's initial surface. We assume that it is consumed in parallel, equidistant layers. When it has burned outward (and simultaneously upward) a distance, r=½(d–n), it cannot go any farther laterally. At that moment it reaches its maximum combustion area. This surface is the sum of the area above the nozzle, the area of the rounded edges[3], and the area of cylindrical sides. Thus,

$$A_{\max} = \frac{\pi\, n^2}{4} + \left(2\pi\, r^2 + \frac{\pi^2 n\, r}{2} \right) + \pi\, d\; h_{\text{cyl}}$$
$$A_{\text{noz}} = \frac{\pi\, n^2}{4} \qquad (2)$$

and

$$f_{\max} = 1 + \frac{8\, r^2 + 2\pi\, n\, r + 4\, d\; h_{\text{cyl}}}{n^2} \qquad (3)$$

From this, we find the height of the combustion chamber:

$$h_{\text{cyl}} = \frac{d\left(f_{\max} - 2\alpha^2 - 3 + \pi \right)}{4\alpha^2} + \left(1 - \frac{\pi}{4} \right) n \qquad (4)$$

where $\alpha = d/n$ is the important ratio of casing diameter to nozzle diameter.

As we shall see in equation 21 below, $\alpha^2 = f_{\min}$ is the other principal parameter. Thus,

$$h_{\text{cyl}} = \frac{d\left(f_{\max} - 2 f_{\min} - 3 + \pi \right)}{4 f_{\min}} + \left(1 - \frac{\pi}{4} \right) n \qquad (5)$$

Whether or not the fuel burns in a precise parallel manner, as we have assumed, does not matter. The reason is the semi-empirical way in which $f_{\max}$ and $f_{\min}$ are treated. Their values are *chosen*, based on some guidelines and on some testing. Therefore, when such experimentally-adjusted parameters are used in the formula, the resulting chamber height becomes as accurate as the user wants it to be.

Conical Cavity

If the spindle tool has a slight taper (for easier removal after ramming), then the combustion cavity becomes the frustrum of a cone as in Figure 3. Here, the height of the cavity is h_{con}, and the narrower diameter at the top of the cavity is δ. The maximum combustion area $A_{\max}$, in this case, is

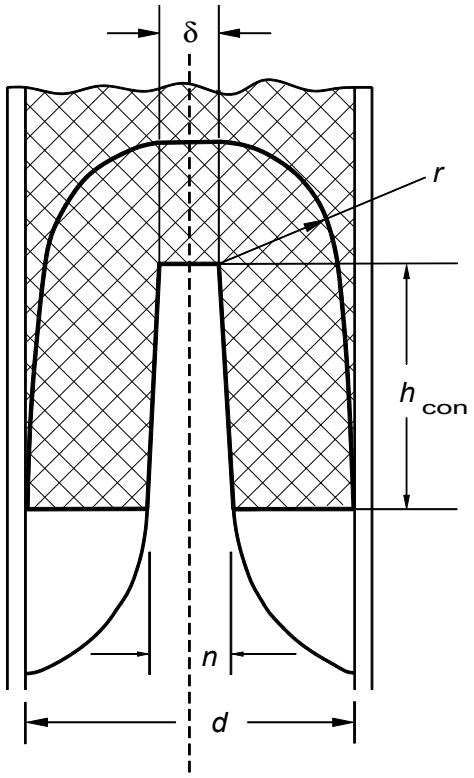

Figure 3. Cross section of a rocket motor with a conical combustion cavity.

$$A_{\max} = \frac{\pi\delta^2}{4} + \left(2\pi\, r^2 + \frac{\pi^2 \delta\, r}{2} \right) + \frac{\pi\left(d^2 - \kappa^2 \right)}{4} \sqrt{1 + \left(\frac{2\, h_{\text{con}}}{d - \kappa} \right)^2} \qquad (6)$$

where

$$\kappa = 2\, r + \delta \qquad (7)$$

The height of the conical combustion chamber is

$$h_{\text{con}} = \frac{n - \delta}{2} \sqrt{\left[\frac{n^2 f_{\max} - \delta^2 - 2\left(d - n \right)\left(d - n + 1/2\pi\delta \right)}{2d\left(n - \delta \right) - \left(n - \delta \right)^2} \right]^2 - 1} \qquad (8)$$

But we have specified that the conical taper is gradual. Therefore, the quantity $n - \delta$, is small,

and the formula can be simplified considerably by ignoring the $(n - \delta)^2$ term and the 1. The resulting approximate chamber height is

$$h_{\text{con}} \approx \frac{d\, f_{\max}}{4 f_{\min}} - \frac{\delta^2 - 2(d-n)(d-n+1/2\pi\delta)}{4\, d} \tag{9}$$

This approximation gives values that differ from equation 8 by, at most, only a few tenths of a millimeter. And since $f_{\max}$ and $f_{\min}$ will be adjusted experimentally anyway, such differences are insignificant.

As in the cylindrical case, these semi-empirical formulas remain useful even though there may be flaws in the motor's geometry or unevenness in the fuel's burning.

The End-Burning Region

When the combustion of fuel has reached far enough up the cartridge so that the burning surface is essentially the flat cross-sectional area of the rocket tube, the thrust remains constant until the fuel is exhausted. Under these conditions, many important properties of the motor can be calculated. The necessary formulas are derived from the thermodynamics of the fuel and of its combustion products, and they contain other adjustable parameters. A fundamental explanation of thermodynamics is, of course, beyond the scope of this paper. But we will use only two abstract quantities that would require such explanations.

The first of these is k, the "heat-capacity index" for the combustion products. For solid fuel mixtures, this index has been found[4] to be of the form

$$k = 1.30 \left(\frac{T_c}{273} \right)^{-0.032} \tag{10}$$

where T_c is the absolute temperature of the combustion chamber. For commercial Black Powder, T_c can be taken as 2300 K. T_c ranges from 1150–2300 K for other mixtures. But k does not vary much (1.21 to 1.24).

The other is the "gas parameter" for the combustion products R (in J/kg·K). It can vary greatly for fuels with potassium nitrate as the oxidizer. R is related to the power (or energy content) of the fuel E:

$$R = \frac{E}{k\, T_c} \tag{11}$$

And since E has values[5] in the range of 230–280 kJ/kg for Black Powder, the resulting R's can be anywhere from 100 to 160.

With these two parameters calculated, we can now derive some of the quantities that describe the rocket motor's performance.

The whole point of rocketry is to create a gas pressure P_c in the combustion chamber that is large enough to move the motor but not large enough to cause an explosion. P_c (in Pa) can be found with the formula

$$P_c = \frac{m_f \sqrt{R T_c}}{t \cdot b \cdot A_{\text{noz}}} \tag{12}$$

where the parameter b is a function[6] of k:

$$b = \sqrt{k \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} \tag{13}$$

Since k is nearly constant, so is b; it only varies between 0.651 and 0.656.

In equation 12, m_f is the mass of fuel (in kg) to be consumed in the motor, and t is the time (in s) that the motor will operate. One of these two numbers is chosen by the motor designer. The other is then specified within the following calculations:

The combustion velocity U, in m/s, (which depends on P_c) is

$$U = U_o \left(P_c \times 10^{-5} \right)^{\nu} \tag{14}$$

where U_o, the combustion velocity at 0.1 MPa (1 atm), varies from 8.8 to 12.1 mm/s (0.0088 to 0.0121 m/s), and ν, the pressure exponent, ranges from 0.5 to 0.24. U_o and ν can be taken as 12.1 and 0.24, respectively, for commercial Black Powder. The end-burning area A_{end} is then found as a function of U and of the density of the fuel ρ:

$$A_{\text{end}} = \frac{\pi\, d^2}{4} = \frac{m_f}{U \cdot t \cdot \rho} \tag{15}$$

The fuel density depends on how the rocket motor is constructed (see Table 1).

Table 1. The Density of Black Powder Fuel Resulting from Various Construction Techniques.

Fuel Compaction Method	ρ (g/cm^3)
Ramming	1.2–1.3
Screw press	1.3–1.5
Hydraulic press	1.5–1.8

The specific impulse I_{sp}, in s is the standard measure of a rocket's power.[7] It is calculated with the formula

$$I_{sp} = \frac{1}{g}\sqrt{\frac{2k}{(k-1)} R\ (T_c - T_o)} \tag{16}$$

where g is the gravitational constant, 9.8 m/s^2 and T_o is the temperature of the combustion gases after they have escaped the nozzle

$$T_o = T_c \left(\frac{P_o}{P_c}\right)^{\frac{k-1}{k}} \tag{17}$$

and where P_o is taken as atmospheric pressure, or 0.1 MPa (1 atm).

The average thrust or propulsion force F_{ave}, in N, is

$$F_{ave} = \frac{m_f g\ I_{sp}}{t} \tag{18}$$

The total impulse I_{tot} is of great importance in classifying the motor for FAI competition:

$$I_{tot} = t\ F_{ave} = m_f g\ I_{sp} \tag{19}$$

Finally, the nozzle diameter can be calculated in terms of f_{min}, the ratio of the minimum combustion area $A_{min} = A_{end} = \frac{1}{4}\pi d^2$ to the nozzle area $A_{noz} = \frac{1}{4}\pi n^2$. Thus,

$$n = d\sqrt{\frac{1}{f_{min}}} \tag{20}$$

This verifies the assertion that we made earlier in the formulas for the heights of the variously-shaped combustion chambers:

$$\alpha^2 = \frac{d^2}{n^2} = f_{min} \tag{21}$$

We have now presented everything necessary for anyone to design a Black-Powder-fueled, model-rocket motor. We summarize, in Table 2, all the adjustable parameters used in this theory together with workable upper and lower bounds for their Black Powder values. These values are given in SI units, but any consistent set of units may be used.

Sample Calculations

Suppose we wish to design a rocket motor with an inside diameter of 0.012 meters (half an inch), and we want it to operate for 2 seconds. We anticipate, of course, that different fuel mixtures will produce different results. To get a feel for the possibilities, let us calculate the properties of two example motors using Black Powder of vastly disparate power. In the first example, we will use some very good commercial Black Powder, perhaps military surplus, for which all the values in the last column of Table 2 apply. We will compact it with a hydraulic press so that it will attain a density of 1720 kg/m^3. In the second example, we will use hand-made meal that has the parameters given in the next-to-last column of Table 2 (except f_{min} will be taken as 36). We will ram it by hand to a density of only 1270 kg/m^3.

Table 2. The Semi-Empirical Parameters Appearing in This Theory and Their Variations Depending on the Quality of Black Powder Used as Fuel.

Parameter	Symbol	Poor-Quality, Hand-Made	High-Grade, Commercial
Maximum area ratio	f_{max}	100	44
Minimum area ratio	f_{min}	50	18
Combustion temperature (K)	T_c	1150	2300
Energy content of fuel (J/kg)	E	230,000	280,000
Combustion rate at 1 atm (m/s)	U_o	0.0088	0.0121
Pressure exponent	ν	0.5	0.24
Density of the fuel (kg/m^3)	ρ	(*see Table 1*)	

Table 3. Calculated Results for a 12 mm Motor that Operates for 2 Seconds on (1) Commercial Black Powder Compressed to a Density of 1.72 g/cm^3, or (2) Hand-Made Powder Rammed to a Density of 1.27 g/cm^3.

Calculated Quantity	Symbol	Example 1	Example 2
Heat capacity index	k	1.21	1.24
Gas Parameter (J/kg·K)	R	100	161
Nozzle diameter (mm)	n	2.83	2.00
Height of cylindrical cavity (mm)	h_{cyl}	1.96	2.77
Height of conical cavity from eqn. 8 (mm)	h_{con}	2.19	2.94
Height of conical cavity from eqn. 9 (mm)	h_{con}	2.17	2.92
Ratio of casing diameter to nozzle diameter	α	4.24	6.00
Mass of fuel (g)	m_f	6.1	6.1
Pressure in combustion chamber (MPa)	P_c	0.358	0.637
Combustion velocity (mm/s)	U	16.4	22.2
Specific impulse (s)	I_{sp}	74.0	77.4
Total impulse (N s)	I_{tot}	4.43	4.63
Average thrust (N)	F_{ave}	2.21	2.31

Table 3 gives the results of the calculations. The heights of both cylindrical and conical cavities are determined in each example. (For the conical cases, δ was taken as 0.9 n). Note that in both examples, the heights of the conical cavities are greater than the cylindrical ones. That is to be expected since it takes a taller cone to have the same area as a cylinder with an equal base. But the differences in height are not all that large. Indeed, for most conical cavities of gradual taper, adjusting the semi-empirical parameters in equations 8 or 9 or even in (cylindrical) equation 5 will lead to motors that are just as good. Note also that, although the motor in Example 2 has the poorer fuel, the combination of a smaller nozzle diameter and a larger

combustion cavity gives it superior performance. The greater fuel density in the Example 1 motor, however, makes it the more reliable of the two.

Conclusion

This theory supplies the necessary know-how for educated amateurs to design Black-Powder rocket motors, whether large or small. And, after building and testing only a few prototypes, it allows them to produce model rockets that perform to their satisfaction.

Here is the procedure: Estimate the intended fuel's power, and choose an initial set of parameters from Table 2. Construct three test motors. Build the first with f_{max} equal to the original guess. Make the other two with f_{max} +10 and f_{max} −10, respectively. Leave all the other parameters, including f_{min}, the same. Test these motors. Since their performance is uncertain, do it under conditions of great prudence and extreme caution; that is, allow for the worst possible failure in any one motor or in all three. See which of them performs best. If that one is satisfactory, the testing phase is complete. If not, test further motors, and focus in, with ever increasing safety and predictability, on ideal performance.

The process is simple and secure. Only the first motors need be an adventure into the unknown. And in the end, anyone can thrill to the lift-off and flight of their own rocket.

Acknowledgment

We thank Ed Brown and Scot Anderson for their careful reading of the manuscript and their insightful comments concerning its content. They improved this article.

References

1) Adapted from E. J. Clinger, *Rockets, Such an Easy Thing!*, Archangelskoye Oblastnoye Aerocosmicheskoye Otdeleniye, Archangelsk, Russia, 1990, Part III (in Russian).

2) M. F. Dyunze and V. G. Zhimolokhin, *Solid-Fuel Rocket Motors for Space Systems*, Mashinostroyeniye, Moscow, 1982 (in Russian). The symbols, which come mainly from this source, are sometimes translated and other times transliterated. The resulting notation may be unconventional to rocket experts in either language.

3) We are indebted to A. David Allen and other members of the Ricks College mathematics department for helping us determine this area. (In the conical case, the area should really begin at a height $h > h_{con}$ where the cone becomes tangent to the curve. Equation 6, therefore, represents a slight underestimation of A_{max}. The effects of this approximation, however, are negligible.

4) Dyunze and Zhimolokhin, *op. cit.*, pp 55–57.

5) B. V. Orlov and G. Yu. Mazing, *The Thermodynamic and Ballistic Basis for the Design of Solid-Fuel Rocket Motors*, Third ed., Mashinostroyeniye, Moscow, 1979 p 391 (in Russian).

6) Dyunze and Zhimolokhin, *op. cit.*, pp 68–69.

7) See, for example, *The McGraw-Hill Encyclopedia of Science and Technology*, Seventh ed., McGraw-Hill, New York, Vol. 17, 1992, pp 211–212.

Flow Agents in Pyrotechnics

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ABSTRACT

Presented is a brief description of the use of flow agents in pyrotechnics. Examples of the use of several agents are described and a simple test for flowability is presented.

Keywords: pyrotechnics, flow agents, flowability, silica, aluminum oxide, carbon black

Pyrotechnic compositions most frequently comprise an intimate mixture of various particulate materials. These mixtures may, or may not, include a substance used as a binder.

One common method of utilizing these mixtures is to load them as a loose powder into some outer container and use as is. An example of this would be a concussion mortar, where a loose powdered composition sits at the bottom of an open cavity. Another common method for using these mixtures is to consolidate them in a confining outer container. An example of this would be a fountain. Both of these usages are simplified if the powdered material being used flows, relatively, freely from a storage container to the container of use. But, it is an unfortunate fact that many, if not most, pyrotechnic compositions have poor flow characteristics, or a tendency to "cake" on storage.

Over the last few hundred years, a number of methods have been developed to alleviate these problems. Of these, perhaps the oldest is slugging (as it is termed in the pharmaceutical industry). In this method the composition is formed into ill-defined pressed forms and then gently crushed to a finer condition. This method has the further advantages of increasing the "as used" density of the, now granular, material, and allowing the selection of the size of the granules to be used. This, of course, is the method used in making Black Powder. A similar method involves wetting the composition with some liquid (which may, or may not, be a solvent for one, or more, of the ingredients), and forming suitable-sized agglomerants from the wetted composition. The granules formed are then, typically, dried before use. The apparent density may also be slightly increased using this method.

However, both of the above methods require substantial processing effort to accomplish. And, for a composition such as a flash powder, may yield a material that is unsuitable for the intended purpose.

Another method to achieve suitable flow characteristics is to add a flow agent to the composition. Most flow agents act as either "ball bearings" by coating the particles of the composition, or to conduct/remove attractive static electrical charges, or both.

Probably the most common agent is silicon dioxide produced by "fuming". This process involves injecting silicon tetrachloride into an oxy-hydrogen flame. It results in sub-micron silica particles having a large surface area (>100 m^2/g). This silica product may then, if desired, be treated with an organo-silane. This treatment results in a hydrophobic material, as opposed to the untreated hydrophilic silica surface, which may lessen the effects of ambient humidity, or moisture, on the composition.

Two facts should be kept firmly in mind when contemplating using either of these two types of fumed silica:

The untreated silica, having a large surface area, can adsorb large amounts of water prior to using it in the mixture.

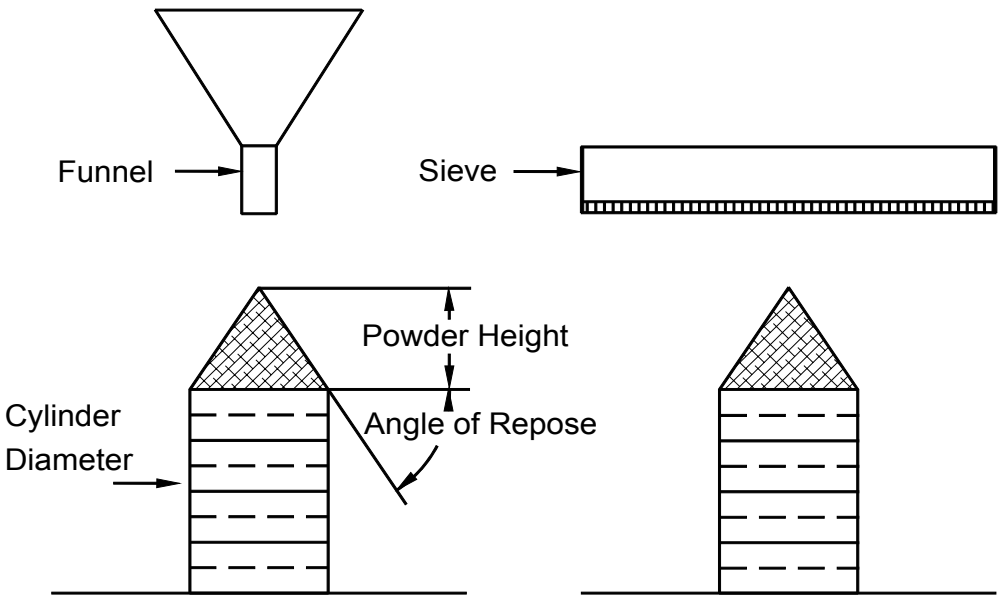

Figure 1. Determining the Angle of Repose:
tan (Angle of Repose)=[Powder Height/(0.5×Diameter)]

The treated silica, being hydrophobic, will make subsequent aqueous processing more difficult.

Other materials that may be used in similar applications are fine aluminum oxide (produced in a similar process as the silicas) and some carbon blacks. Carbon black and fine aluminum oxide have effects beyond those of silica. Conductive carbon blacks can serve to internally neutralize static charges by conduction. Aluminum oxide always develops a positive surface charge which may serve to neutralize a developed negative charge on some materials.

In using any of the above products, it will generally be found that, if the product is suitable for the use, only a small amount will be needed. Manufacturers' recommendations range from about 0.05–0.2% for potato starch up to 4–6% for zinc oxide. The author has found that, for many pyrotechnic compositions, the range is from about 0.25 to 2%.

Since these products are used as a coating for some other powder, they are usually mixed using a low shear method, such as tumbling. A user may often find that there is some particular process and sequence that works better than another for a specific application. Such differences may be adding the silica to the mixer first or second, using only screening, tumbling then screening, etc.

Achieving the best results using the least flow agent is a field fraught with possibilities.

Another use for fumed silica is to form thixotropic gels with various liquids. This property is used to make greases, rocket propellants, cosmetics, paints, and a whole host of other end products. Using the silicas in this way typically requires a high-shear mixer to form the silica/liquid gel.

One quantitative measure of goodness for flow is the angle of repose of the material in question. This angle is one of the most commonly accepted measures of flowability for solids and is used by both chemical process and civil engineers. A simple test may be easily performed by the pyrotechnician using a cylinder and funnel, or screen, and a height measuring instrument (Figure 1). The material to be tested is carefully poured, or sieved, onto the cylinder where it will collect and form a conical heap. Since the diameter at the base of the cone is a constant, the easily measured height of the cone yields the angle of repose for the tested material. Under some circumstances, it may be de-

Table 1. Results of Using Flow Agents.

Material	Angle of Repose
Flowers of Sulfur	
no additive (material was very difficult to get through the funnel, and formed varying peaks on the heap)	> 80
0.5% Cabot XC72R	38.1
1.0% Cabot TS720 (material showed a great amount of "static cling")	31.6
0.25% Cabot XC72R + 0.5% Cabot TS720 (no cling)	31.8
Potassium Nitrate	
no additive	57.6
1% Degussa Aerosil 200	44.0
1% Degussa Aerosil R972	39.1
1% Cabot XC72R	42.4
0.5% Cabot XC72R + 0.5% Degussa Aerosil R972	31.7

sirable to subject the cone of material to some small reproducible vibration or shock to obtain a more meaningful result.

Some representative data is given here to help the potential user of flow agents.

The technique used to obtain the data was as follows:

1. The base materials used were
   Potassium Nitrate, technical grade ground to pass 70% through a US Standard –325 mesh sieve
   Flowers of Sulfur — no other specification.
2. Flow agents used were
   Cabot XC72R conductive carbon black
   Cabot TS720 organo-silane treated silica
   Degussa Aerosil 200 silica
   Degussa Aerosil R972 organo-silane treated silica
3. The base material and the flow agents were dried at 70 °C for 16 hours.
4. A measurement of the angle of repose was made on the base material. See Figure 1.
5. Several hundred grams of base material was weighed and the selected weight of flow agent was added to it in a plastic cup. A lid was secured on the cup, and the cup was shaken by hand for 30 seconds. The mixture was then passed through a US Standard –100 mesh sieve, and again shaken in the cup for 30 seconds.
6. A measurement was then made on the mixture.

The results are shown in Table 1.

While there has been no attempt, here, to exhaustively detail how these agents may be used, it should be obvious, from this brief description, that flow agents are a useful item to incorporate in the pyrotechnicians armentarium.

The author wishes to thank Cabot Corporation, Degussa Corporation, and Luna Tech, Inc. for their help.

Hazard Analysis for the Manufacture of a UN Gas Generant

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ABSTRACT

The Yoshida Hazard Analysis (YHA) was applied to the manufacturing of a gas generant composed of Urazole, a metal nitrate (Urazole/MNO_3) and other materials. The safety hazards of the materials used in the manufacturing process were identified and evaluated in a hazard catalog, and the risks of each unit operation in the process were plotted on risk profiles for normal operations, operations which deviated from normal, and corrected operations. In the course of making these risk profiles, the hazards of operations that deviate from the normal were identified and measures for safe operations and handling of materials were instituted.

Keywords: hazard analysis, gas generant, risk profile, urazole, airbag

1. Introduction

Originally, the AK (Azodicarbonamide [ADCA]/$KClO_4$) gas generant for automotive airbag inflators was developed by the author's group to replace the azide-based gas generant.[1] The so-called UN (i.e., Urazole/MNO_3) gas generant was then developed as an improved system. The UN gas generant is more stable and has a lower combustion temperature than the AK gas generant. The qualities of stability and lower combustion temperature are advantageous for the safety and performance of gas generants. In developing the new gas generant system, the fire and explosion hazards of the composition, as well as, of the raw materials were evaluated. It has been confirmed that the Urazole and the UN composition are safer than the ADCA and AK composition.[2]

Herein we describe the results of the hazard analysis for the manufacturing process for the new gas generant. This has been done using the experimental results from hazard evaluations. The YHA technique AK gas generant,[3] the Process Safety Management (PSM) of the Occupational Safety and Health Administration (OSHA),[4] the Zurich Hazard Analysis (ZHA) of the Zurich Insurance Company[5] and the United States Military Standard[6] were referred to in developing the YHA.

2. Yoshida Hazard Analysis for Energetic Materials (YHA)

2.1 Outline of the YHA

The YHA is a method for preventing accidents caused by energetic materials during their manufacturing and handling. The YHA consists of a risk evaluation which uses experimental data on energetic materials and three risk profiles: one for normal operations, one for operations deviating from normal, and one for corrected operations. For these purposes, risk is defined as follows:

Risk = (probability of occurrence) × (severity of damage)

The following items are evaluated in the YHA:

1) The scope of the project
2) Diagrams of the process, the flow of materials and the equipment

3) Material safety information
4) Process technology information
5) Hazard identification and risk catalog
6) Risk profiles
7) Safety measures
8) Prevention of deviation from normal operation and corrected risk profiles
9) Conclusions

2.2 Probability of the Occurrence of Fire and Explosion

It is assumed that the probability of occurrence of fire and explosion is a function of the sensitivity and mode of handling of hazardous materials including pyrotechnic compositions, intermediates and raw materials. Expressed symbolically,

$$P = f(S,H)$$

where P is the probability of occurrence of fire and explosion, S is the sensitivity of the materials, and H is the mode of handling of materials. The sensitivity of materials is divided into four categories corresponding to the probability of the occurrence of an event:

Level	Probability	Sensitivity
A	Frequent	High
B	Occasional	Medium
C	Remote	Low
D	Impossible	None

2.3 Criteria of Sensitivity

A high-sensitive material may be ignited frequently during ordinary handling. A medium-sensitive material requires a strong stimulus to be ignited. A low-sensitivity material will not be ignited nor initiated without very high friction, high impact, shock, electric spark, contact with a hot object or high temperature. After many experiments,[2,7–14] criteria for sensitivities have been determined for explosives, propellants and pyrotechnic compositions (Tables 1–5).

2.4 Effect of an Event: Degree of Damage

The degree of damage caused by fires or explosions of hazardous materials is assumed to be a function of the violence of the fire or explosion, the amount of material involved and environmental conditions. Symbolically,

$$D = g(V,M,E)$$

Table 1. Criteria for Impact and Shock Sensitivity.

Level	Sensitivity	Test	Criterion	Ref.
A	High	Drop Ball (Direct Impact)	$E_{50} \leq 1.0$ J	7
		Shock Ignitability (No. 0 Det.)	$I_{50} \geq 5$ mm	8
B	Medium	Shock Ignitability (No. 0 Det.)	$I_{50} < 5$ mm	8
		VP30 PVC Tube (No. 6 Det.)	Propagation	10
C	Low	VP30 PVC Tube (No. 6 Det.)	No Propagation	10
		UN Gap (160 g Booster)	Propagation	11
D	No	UN Gap (160 g Booster)	No Propagation	11

Table 2. Criteria for Friction Sensitivity.

Level	Sensitivity	Test	Criterion	Ref.
A	High	BAM Friction	$M_{50} \leq 1$ kg	12, 14
B	Medium	BAM Friction	1 kg $< M_{50} \leq 10$ kg	12, 14
C	Low	BAM Friction	10 kg $< M_{50} <$ 36 kg	12, 14
D	None	BAM Friction	36 kg $< M_{50}$	12, 14

Table 3. Criteria for Electric Spark Sensitivity.

Level	Sensitivity	Test	Criterion	Ref.
A	High	For High-Sensitivity	$E_{50} \leq 1.0$ J	13, 15
B	Medium	For High-Sensitivity	1.0 J < E_{50}	13, 15
		For Medium-Sensitivity	E_{50} < 10 J	13, 15
C	Low	For Medium-Sensitivity	10 J < E_{50}	13, 15
			E_{50} < 100 J	13, 15
D	None	For Medium-Sensitivity	100 J < E_{50}	13, 15

Table 4. Criteria for Ignition by Contact with Hot Objects.

Level	Sensitivity	Test	Criterion	Ref.
A	High	Cerium–Iron Spark	Ignition	14
B	Medium	Cerium–Iron Spark	No Ignition	14
		Conical pile (Ni–Cr)	Ignition	2
C	Low	Conical pile (Ni–Cr)	No Ignition	2
		VP30 PVC Tube (5 g Ignitor)	Ignition	2
D	None	VP30 PVC Tube (5 g Ignitor)	No Ignition	2

Table 5. Criteria for Thermal Stability (Tentative).

Level	Sensitivity	Test*	Criterion**
A	High	SC—DSC	T_{DSC} < 100 ºC
B	Medium	SC—DSC	100 ºC <T_{DSC} < 200 ºC
C	Low	SC—DSC	200 ºC <T_{DSC}
D	None	SC—DSC	No Exotherm

* SC = Sealed Cell
DSC = Differential Scanning Calorimetry

** T_{DSC} = DSC onset Temperature

where D is the degree of damage; V, the violence of the event; M, the amount of hazardous materials involved; and E, the environmental conditions.

To assign materials to hazard ranks according to the violence of the fire or explosion and the amount of materials involved, materials are classified as follows:

1) Primary explosives, which show a deflagration to detonation transition upon ignition.
2) Semi-primary explosives, which show a deflagration to detonation transition under some conditions after ignition.
3) Detonating explosives, which explode after initiation with a No. 6 detonator.
4) Deflagrating explosives, which burn with high speed without a shock wave when ignited or initiated by shock, or which detonate by strong initiation under tight confinement.
5) Combustible materials, which burn with low speed after ignition.
6) Poorly-combustible materials, which burn only when an external fire is involved.
7) Non-combustible materials.

The range of quantities of materials corresponding to the classification and damage ranking is listed in Table 6. The effect of environmental conditions will be taken into considera-

Table 6. Damage Ranks, Degree of Damage and Ranges of Amounts (m) of Materials.

Rank	Damage	Range of Inventory		
		Primary Explosives	Semi-Primary Explosives	Detonating Explosives
I	Catastrophic	100 g ≤ m	1.0 kg ≤ m	10 kg ≤ m
II	Critical	10 g ≤ m < 100 g	100 g ≤ m <1.0 kg	1.0 kg ≤ m < 10 kg
III	Marginal	1.0 g ≤ m <10 g	10 g ≤ m < 100 g	100 g ≤ m < 1.0 kg
IV	Negligible	m < 1.0 g	m < 10 g	m < 100 g
Rank		Range of Inventory		
	Deflagrating Explosives	Combustible Materials	Poorly-Combustible Materials	Non-Combustible Materials
I	100 kg ≤ m	m = ∞	m = ∞	m = ∞
II	10 kg ≤ m < 100 kg	1.0 t ≤ m	m = ∞	m = ∞
III	1.0 kg ≤ m < 10 kg	100 kg ≤ m <1.0 t	m = ∞	m = ∞
IV	m < 1.0 kg	m ≤ 100 kg	m = ∞	m = ∞

tion when the YHA is applied to an actual process.

2.5 Risk Profile and Acceptable Levels

The risk profile and acceptable levels are shown in Figure 1. In this case, two acceptable levels are defined. One is acceptable without review; the second is acceptable under some restrictions with strict reviewing.

In the YHA, three risk profiles are used. The first is an expected or preliminary profile made with the assumption that process operates normally. The second is made by assuming the

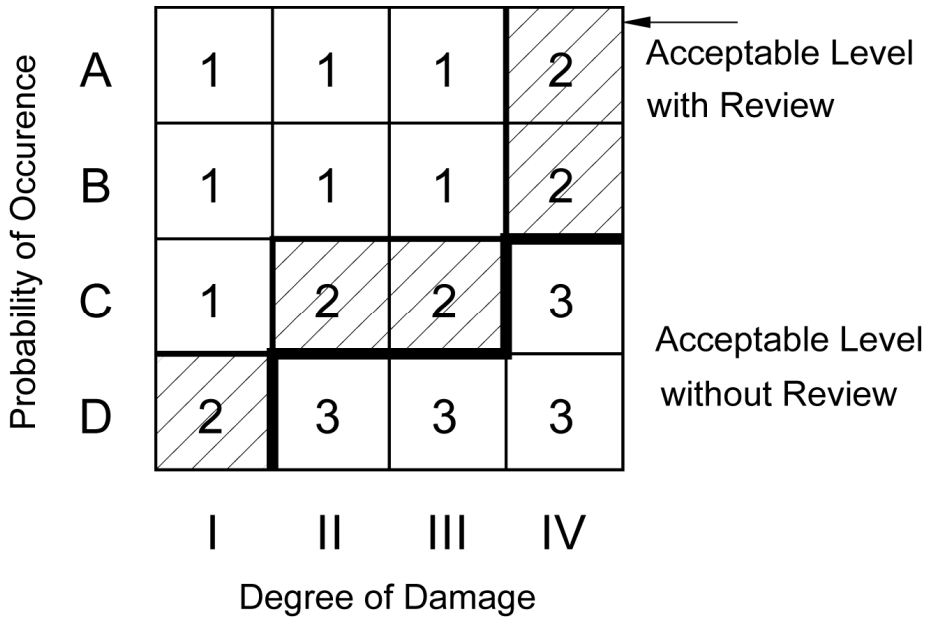


Figure 1. Risk profile and acceptable levels.

worst case of deviation from normal operation. After the second profile is made, safety measures are examined. Finally, a corrected risk profile is made and measures for preventing hazardous deviations from normal operations are shown. This assessment is especially useful for preventing human error.

3. Diagrams of Process and Material Flow and the Equipment

3.1 Flow Diagram of Processes

The flow diagram of the process for the manufacture of a UN gas generant is shown in Figure 2. In mixing raw materials, additive 1 and potassium nitrate (KNO_3) or additive 2 (another oxidizer) should not be mixed directly. If additive 1 is mixed directly with these materials, the resultant combination is highly sensitive and burns violently.

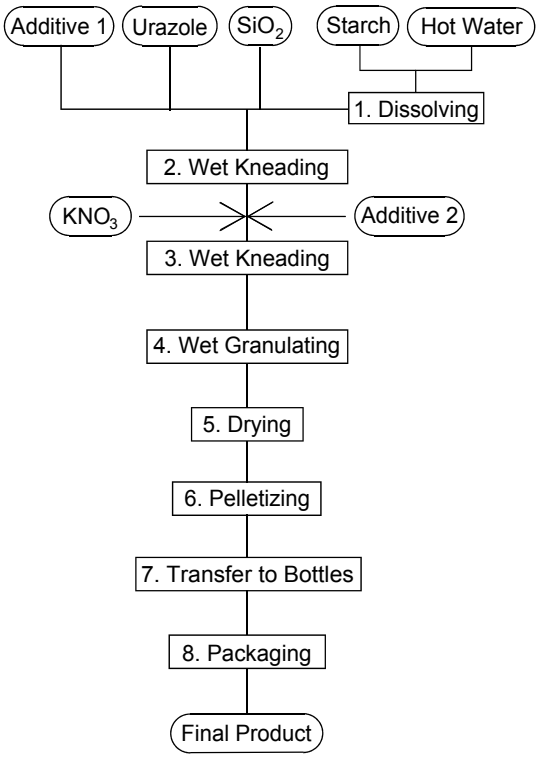


Figure 2. Flow diagram for manufacturing UN gas generant.

3.2 Flow Diagram for Materials

The flow diagram for materials used in the process is shown in Figure 3. The raw materials are Urazole, KNO_3, silicon dioxide (SiO_2), soluble starch, water, additive 1 and additive 2. Additive 1 and additive 2 are classified as fuel and oxidizer, respectively. The intermediates are the dry mixture of Urazole, SiO_2, soluble starch and additive 1, the wet mixture (2) of all raw materials, the wet granules of mixture (2), the dried granules, the dry pellets in bulk, and the dry pellets in bottles. The final products are the packages containing the pellets in bottles.

3.3 Equipment

The primary equipment used in the manufacturing process are a dissolving vessel, a kneading mixer, a granulator, drying ovens and a tabletting machine. The dissolving vessel for the soluble starch has a capacity of approximately 20 liters. It is made of stainless steel and is heated by steam. The mixer is a kneading mixer. The dry Urazole, SiO_2 and additive 1 are fed into the

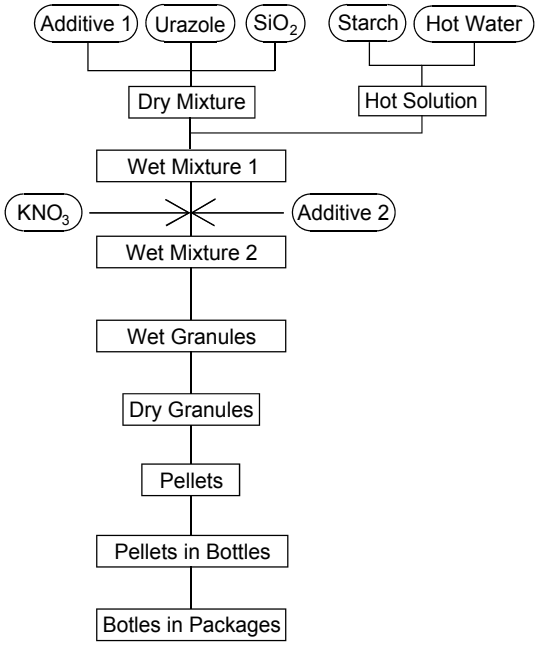


Figure 3. Materials flow diagram for manufacturing UN gas generant.

mixer and are preliminary mixed. The starch solution is added and mixed. KNO_3 and additives are added to the mixture, which is then kneaded thoroughly. The granulator is a screw extruder. The composition in the granulator is wet with water and therefore safe.

The drying oven is a warm air circulating oven equipped with a safety device to prevent overheating. The drying operation is the most hazardous among all the unit operations because the possibility exists that dry granules in bulk will ignite in the oven. The tabletting machine is a rotary type. Friction is high between the pestle and mortar during the tabletting operation, and the decomposition of AK in the machine has been observed. However, the decomposition in the mortar did not affect the outside of the mortar.

4. Material Safety Information

4.1 Sensitivity of Materials

The sensitivity determinations were carried out,[2] and the sensitivity criteria based on this as well as previous work[3] are listed in Tables 1–5. The sensitivity levels of the raw materials, intermediates and products of the UN gas generant are listed in Table 7.

The thermal stability level of UN is ranked "C" because the exothermic onset temperature, T_{DSC} = 260 ºC. If the material is involved in fire or is contacted by a hot object over 200 ºC in temperature for long periods, the material may become hazardous. However, all raw materials used in this process are safe at room temperature.

Insufficient control of the oven's temperature and deficiencies in cleaning the drying oven in addition to changing the composition of the mixture without assessing the stability of new ingredients may contribute to an accident. The pellets described present no problem if they are handled normally.

Table 7. Sensitivity Levels of Materials Used in the Process.

No.	Materials	Impact Shock	Friction	Electric Spark	Hot Objects	Thermal Stability	Note
1	Urazole	D	D	D	D	C	Raw Material
2	KNO_3	D	D	D	D	D	Raw Material
3	SiO_2	D	D	D	D	D	Raw Material
4	Starch	D	D	D	D	D	Raw Material
5	Hot H_2O	D	D	D	D	D	Raw Material
6	Additive 1	D	D	D	D	D	Raw Material
7	Additive 2	D	D	D	D	D	Raw Material
8	Hot Soln.	D	D	D	D	D	Intermediate
9	Dry Mix.	D	D	D	D	C	Intermediate
10	Wet Mix. 1	D	D	D	D	D	Intermediate
11	Wet Mix. 2	D	D	D	D	D	Intermediate
12	Wet Gran.	D	—	D	D	D	Intermediate
13	Dry Gran.	D	—	D	C	C	Intermediate
14	Pellets	D	—	D	C	C	Product
15	Pellets in Bottles	D	—	—	C	C	Product
16	Bottles in Packages	D	—	—	C	C	Final Product

4.2 Combustion Categories, Amounts and Damage Levels of Materials in the Manufacturing Process

The combustible or explosive materials used in the process are:

Poorly-combustible Materials: Urazole, soluble starch, dry and wet mixture of Urazole, SiO_2 and additive 1, wet mixtures of all raw materials and wet granules;

Combustible Materials: dry granules, pellets in bulk, pellets in bottles and bottles in packages.

The risk of dry pellets, pellets in bulk and pellets in bottles must be evaluated. An inventory amount corresponding to one batch from the process is assumed to consist of less than 100 kg at the stage of mixing and less than 20 kg in the drying operation. The combustibility categories, inventory amounts and damage levels for materials in the process are listed in Table 8.

4.3 Effect of Materials on Health and the Environment

Information on the effect of materials used in the process on the health of people in the work place and on the environment was collected. The 50% lethal does (LD_{50}) and the time weighed average–threshold limit value (TLV–TWA) are listed in Table 9. The inhalation toxicity of SiO_2 depends on its particle type, so use of the least toxic form of SiO_2 is recommended.

5. Process Technology Information

The process information is described according to the OSHA standard[4] as follows:

5.1 Flow Diagram for Process

This was presented in Figure 2.

Table 8. Combustibility Categories, Inventory Amounts and Damage Levels of Materials in the Process.

No.	Materials	Combustion Category	Max Batch Inventory	Damage Level
1	Urazole	Poor-Combustible	50 kg	IV
2	KNO_3	Non-Combustible	50 kg	IV
3	SiO_2	Non-Combustible	50 kg	IV
4	Starch	Poor-Combustible	10 kg	IV
5	Hot H_2O	Non-Combustible	20 kg	III
6	Additive 1	Combustible	5 kg	IV
7	Additive 2	Non-Combustible	50 kg	IV
8	Hot Soln.	Non-Combustible	20 kg	III
9	Dry Mix.	Poorly-Combustible	100 kg	IV
10	Wet Mix. 1	Poorly-Combustible	100 kg	IV
11	Wet Mix. 2	Poorly-Combustible	100 kg	IV
12	Wet Gran.	Poorly-Combustible	100 kg	IV
13	Dry Gran.	Combustible	20 kg	III
14	Pellets	Combustible	20 kg	III
15	Pellets in Bottles	Combustible	100 kg	IV
16	Bottles in Packages	Combustible	100 kg	IV

Table 9. LD_{50} and TLV–TWA of Raw Materials.

Materials	Toxicity LD_{50} in mg/kg(Animal)	Threshold Limit Values TLV–TWA in mg/m^3 ACGH
Urazole	NA*	NA*
KNO_3	NA*	NA*
SiO_2	3600(Rat)	10
Starch	No	NA*
Water	No	NA*
Additive 1	NA*	NA*
Additive 2	551(Mouse)	NA*

NA* = Not Available.

5.2 Process Chemistry

No chemical reaction takes place during the manufacturing process.

5.3 Maximum Intended Inventory

A maximum intended inventory of 100 kg per batch is expected. In drying operations, a 20 kg batch is assumed.

5.4 Safety Limits of the Operation

(a) Temperature (T)

80 ºC < T < 100 ºC
for dissolving the soluble starch

70 ºC < T < 90 ºC
for drying the granules

0 ºC < T < 40 ºC
for other operations

(b) Pressure

Materials are pressurized in the granulating and tabletting operations. The safety limits for these operations have not yet been set.

(c) Flow Rate

In the granulating and tabletting operations, the flow rates of materials are important factors for considerations of operability as well as hazard. The safety limits for flow rates have not yet been set.

(d) Composition

Changing the composition of the gas generant affects the safety performance of the process. The composition may vary by a maximum of 5% from the normal composition.

5.5 Evaluation of Consequences of Deviations from Normal Operation

(a) Deviations in the Composition

A change in the oxygen balance affects the concentrations of CO and NO_x in the effluent gas. A deviation in the amounts of additive 1 and 2 affects the safety by changing the combustion properties. If the water content of the mixture deviates, the granulating process becomes more difficult to operate.

(b) Deviations in the Operating Conditions

When the operation of the tabletting machine deviates from normal, the toughness and density of the formed pellets changes, and as a result the properties of their combustion are affected.

(c) Deviation in the Amount of Material

Overloading the drying oven causes granules to spill, which may in turn cause accidental ignition. If a large amount of dry granules and pellets is ignited accidentally, the fire is hazardous and may damage individuals and property. If the amount of such materials is limited, any resultant fire can be easily extinguished with a water spray.

(d) Deviation in Pressure

The drying oven should be designed such that pressure does not increase when an accidental fire occurs. The burning speed of a small amount of granules of the UN gas generant is slow under atmospheric pressure, but a large amount burns quickly if under high pressure.

(e) Deviation in Temperature

If the temperature in the drying oven rises too high, dry granules or dust may ignite. If dust is allowed to accumulate on the overheated heater in the oven, it may ignite.

6. Hazard Identification and Risk Catalog

The potential hazards in the manufacturing process for the UN gas generant were identified and ranked by the sensitivity, the combustibility and the amount of material used in the process. Using the results of the hazard identification and ranking, a risk catalog was made for the process as listed in Table 10.

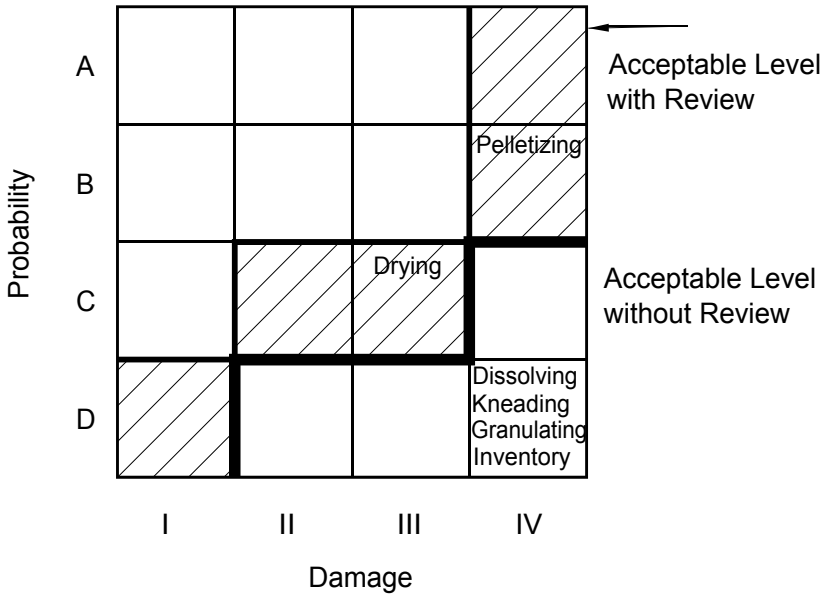
7. Risk Profiles for Normal Operations and Deviations

The risk profiles for normal operations and deviations are shown in Figures 4 (a) and (b), respectively. All operations fall within the acceptable level with review, and only the drying and tabletting operations are outside the acceptable level in the absence of review.

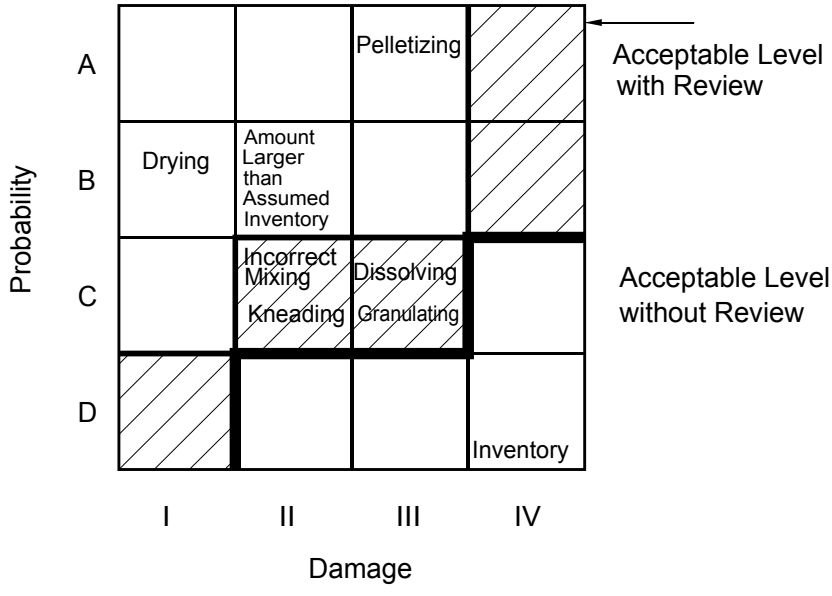
Table 10. Risk Catalog for Operations in the Process.

No.	Operation	Normal	Hazardous Material	Risk Rank	Note
1	Dissolving	Normal	Hot Water	III C	Spill and Scald
		Deviated	Hot Water	IV C	No Problem
2	Wet Kneading	Normal	Wet Mix. 1	IV D	
	No Problem	Deviated	Dry Mix. 1	IV D	Dry Mixing
3	Wet Kneading	Normal	Wet Mix. 2	IV D	
	No Problem	Deviated	Dry Mix. 2	IV C	Dry Mixing
2,3	Dry Mixing	Normal			
		Deviated	Add. 1 + KNO_3	II C	Incorrect Mixing
4	Granulating	Normal	Wet Mix. 2	IV D	No Problem
		Deviated	Dry Mix. 2	III C	Overheating and Ignition
5	Drying	Normal	Dry Gran.	III C	Overheating and Ignition
		Deviated	Dry Gran.	I B	Overheating and Ignition
6	Pelletizing	Normal	Dry Pellets	IV B	Decomp. in Motors
		Deviated	Dry Gran.	III B	Decomp. and Ignition
7	Transfer to	Normal	Pellets	IV D	
	Bottles	Deviated	Pellets	IV D	
8	Packaging	Normal	Pellets	IV D	
		Deviated	Pellets	IV D	
9	Fire	Normal	Gran. and Pellets	III	Normal Amount
		Deviated	Gran. and Pellets	II	Larger Amount than Normal
10	Hot Matter	Normal	Gran. and Pellets	III	Normal Amount
		Deviated	Gran. and Pellets	II	Larger Amount than Normal

Many case histories are known involving hazards in the drying operations of energetic materials. Although the UN composition is stable, because of its high exothermic onset temperature, and few possibilities of ignition are expected in normal drying operations, ignitions are still possible in the drying oven. One possibility is that the oven overheats the UN granules. A second possibility occurs if dust from the composition accumulates on the hot surfaces of the oven and ignites. Of course, it is also always possible that the composition may ignite from some unidentified sources.



(a) Risks under Normal Operations



(b) Risks When Handling Deviates from Normal

Figure 4. Risk profiles for manufacturing UN gas generant.

Small quantities of UN granules burn slowly under atmospheric pressure. If the drying oven is well designed, the damage level for granules is ranked at level III. In the granulating operation of an AK composition, decomposition in the mortar of the granulating machine has been observed. This decomposition made noise but did not affect the machine or the outside of the mortar. Such a decomposition may be caused by friction during the normal tabletting operations. Dissolving starch, mixing and kneading the raw materials, granulating the mixture and the amounts of materials involved should not cause accidents if operations are carried out normally.

Among the risks associated with operations that deviate from normal, the highest are associated with the drying operation. The causes of ignition include the use of an incorrectly designed oven, modification of the composition to an unstable one, contamination, and accumulation of dust on the hot surfaces of the oven.

If the oven is maintained improperly, the oven may overheat and the UN composition may ignite. If the inside of the oven is not kept clean, dust from the composition accumulates on hot surfaces and may ignite. If the composition is contaminated with a material which catalyzes a reaction, it may become unstable. If a component of the composition is modified, a safety assessment must be done on the new formulation to establish its stability. These types of deviation from normal operation must be prevented.

Additional problems to be considered are the violence of possible combustion reactions and the severity of the resultant damage. If UN granules are placed in an oven that is not the open design, an accidental ignition and subsequent burning of the granules may blow the oven door off and injure workers. It is crucial to use a properly designed oven for safe drying.

In the tabletting operation, decomposition is inevitable in the mortars of the machine. Decomposition in a mortar normally does not affect the outside of the device, but as the mass of the pellets increases, decomposition in the mortar may propagate and ignite granules outside the machine. Good maintenance and cleaning of the tabletting machine are important for preventing incidents during the tabletting operation.

The filling of bottles with UN pellets and the packaging of the bottles into containers has no risk other than that of external fire. The packaging will not promote fire.

If too high an inventory of the UN powders, granules or pellets is maintained, these materials become a hazard because of their rapid combustion. This is known for the AK gas generant as well.[16] This is especially the case if the generants are sealed tightly in a container. One should avoid both over-inventory and the use of sealed vessels in processing.

If dry raw materials are mixed without adding water, the possibility of ignition exists, and burning the dry mixture may blow the cover of the mixing machine. The damage will be more severe if a machine with tight seals is used.

Workers must be informed of the hazards associated with incorrect mixing of components. For example, mixing oxidizing materials with additive 1 yields deflagrating mixtures. This must be avoided.

Hot water is used in dissolving soluble starch. In general, hot water is handled in a closed system and, therefore, there is little hazard. If a container is broken or inadequate precautions are taken, water may spill and potentially scald those working with it.

The granulating machine may become heated if the water content of the composition is inadequate. The water content of the mixture must be controlled and the machinery must be regularly maintained to insure safe operation.

8. Prevention of Deviations from Normal Operation and Corrected Risk Profile

From the consideration of the risk catalog and profiles of the normal operation and deviations from it, we suggest measures for preventing deviations and for promoting safety of operations at acceptable levels.

8.1 Safety Measures for Drying Operations

Two measures for preventing accidents during the drying operation have been identified. One is preventing the occurrence of ignition in the oven as follows:

1) Select an oven with good temperature control.
2) Select an oven without hot, exposed surfaces.
3) Prevent the accumulation of dust in the oven.
4) Use a composition of known stability.
5) Prevent contamination which makes the composition unstable.

A second is to prevent damage when ignition accidentally occurs:

1) Use an oven without a tight seal.
2) Limit the amount of granules in the oven.
3) Use an oven with a safe door.
4) Prevent anyone from approaching the safety relief opening of the oven when the drying operation is in progress.

8.2 Safety Measures for Inventory

It is important to let involved people know the consequences of deviations in the amount of materials on hand and the necessity of keeping a fixed inventory.

8.3 Safety Measures for the Tabletting Operation

Ignitions in tabletting machines are quite common. It is important that the machine is designed so that ignition does not propagate.

As the tabletting machine is apt to malfunction, appropriate personnel must be in charge of the machine and must maintain it in optimum condition. Workers should be educated and trained in preventing the accumulation of dust, granules and pellets around the machine.

8.4 Safety measures for the Granulating Operation

In the normal operation, granulating is safe because it is carried out on a mixture wet with water. However, the material in the machine may be subjected to excess pressure, friction or high temperature if the amount of water present is inadequate. It is important for appropriate personnel to be aware of these factors and to keep the machine in optimum condition to carry out the granulating operation safely.

8.5 Safety Measures for the Kneading Machine

The order in which raw materials are fed into the kneader must be strictly fixed. Additive 1 should not be mixed directly with KNO_3 or additive 2. The workers must be educated thoroughly in this regard. The kneader sometimes heats up during operation. Excess heating indicates a deviation from normal operations, and it is essential that the cause be determined and removed.

8.6 Safety Measures for Dissolving Starch

The dissolving vessel should have a structure that allows no spills of hot water. This should present no problems if the equipment is correctly designed.

8.7 Corrected Risk Profile

A corrected risk profile for the manufacturing process of a UN gas generant was produced according to the suggestions in this paper and is shown in Figure 5.

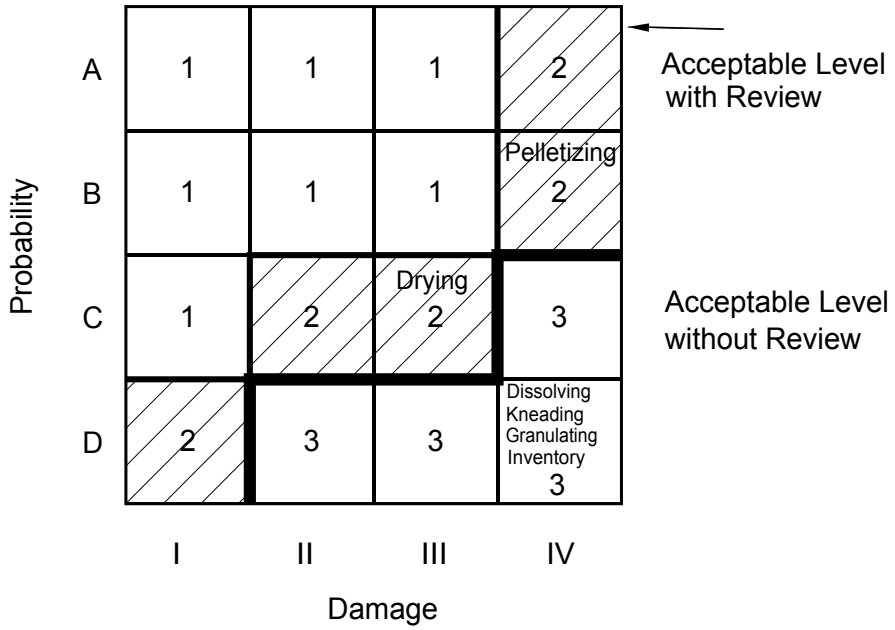


Figure 5. Corrected risk profile for manufacturing of UN gas generant.

9. Conclusion

A hazard analysis has been carried out for the manufacture of a UN gas generant in a batch 100 kg in size. The following conclusions were reached:

1) The UN gas generant can be manufactured safely if the appropriate people have information on the hazards associated with the materials and the normal operations used in the process and avoid deviations from normal operating procedures.
2) The drying operation has the highest associated risk among the operations in the process. The design of the oven, its use, and the thermal stability of the formulation are also important.
3) The order in which the raw materials are blended is important.
4) Good maintenance of the tabletting and granulating machines is crucial.

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Errata — Issue No. 3

Page 39: In the formula, (A_e) should be (A_b).

The correct formula is:

$$P=B\left(\frac{A_b}{A_t}\right)^{\frac{1}{1-n}}$$

Techniques for the Quantitative Analysis of Sulfur and Chlorate in Fireworks Compositions

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ABSTRACT

This paper examines the analysis of pyrotechnic compositions found in fireworks for the presence of sulfur and chlorate ion (ClO_3^-). Admixtures of these two components can produce compositions which have high sensitiveness to mechanical stimuli (e.g., friction and impact), may be thermally unstable, and are not normally permitted in fireworks in the UK. Analytical methods for the admixture have, in the past, been qualitative. Colorimetric techniques have been developed for the quantitative analysis of sulfur and chlorate which use readily available materials and equipment. The techniques have been validated by examining pyrotechnic mixtures with known proportions of sulfur and chlorate. Fireworks compositions have been analysed and varying levels of sulfur and chlorate found.

Keywords: sulfur/chlorate admixture, analysis, fireworks, sulfur, chlorate

Introduction

In the United Kingdom (UK) there has been a long standing prohibition of sulfur/chlorate admixtures in fireworks. Such admixtures are in contravention of Order in Council No. 15 of the UK Explosives Act[1] which prohibits "fireworks containing sulfur in admixture with chlorate of potassium or other chlorate, unless with the consent of and subject to conditions approved by a Government Inspector". This 1894 addition to the 1875 Act was the result of some twenty-eight accidents and eleven deaths which occurred in the period between the Act and the additional legislation and were attributed to sulfur/chlorate admixtures.[2]

During check examinations of fireworks, items may be found for which chemical analysis indicates sulfur/chlorate admixtures. In our work the presence of sulfur and chlorate in firework components was indicated by positive results in all tests described in the British Standard.[3] The methods are only qualitative, however, and need to be supplemented for enforcement or consent purposes by quick and reliable assessments of the levels of the two materials in fireworks compositions.

This paper describes the development and validation of methods to quantitatively assess sulfur and chlorate in fireworks and their component compositions by extending two tests given in the British Standard. The tests developed for quantitative analysis were the anilinium chloride test for oxidiser and the piperidine test for sulfur: both materials generate characteristic colours. In a similar fashion Urone and Bonde[4] have reported that chlorate in well waters could be determined by the colour generated from o-toluidine in concentrated hydrochloric acid.

Experimental

Mass measured during the course of this work can be traced to national standards. Milligram quantities were measured to 0.01 mg, and gram quantities were measured to 0.01 g. Volume measurements were made using Grade A volumetric apparatus, except for 500 µL quantities which were delivered using a fixed volume automatic pipette. Colorimetric measurements were carried out using a CO75 colorimeter (WPA) using gelatine filters with a typical bandpass of 40 nm. Although the methods have not been tested with other colorimeters or visible spectrophotometers, it should be

possible to adapt the techniques for use with other suitable optical devices.

Sample Preparation

A series of samples containing sulfur and an inert material, and chlorate and an inert material were prepared for the initial experiments. Salts, typical of firework compositions, were ground carefully in a clean agate pestle and mortar to form a fine powder and placed in a sample bottle for dispensing. Flowers of Sulfur (Timstar Laboratory Supplies Ltd.) were used as supplied. Specimen formulations were then prepared from dried salts, sulfur and inert material (e.g., talc and sodium chloride) by simple weighing and mixing within the sample tube. Typically 200 mg to 1g of material was prepared for analysis. In the early tests, the specimens were prepared without further additional treatment of the salts, but in later tests the salts were dried prior to specimen preparation.

Consolidated firework compositions were, generally, carefully pared to produce a fine powder for extraction. Where small hard grains were encountered, single grains were ground carefully in an agate pestle and mortar to produce fine powder. Firework compositions were analysed without drying to avoid heating potentially thermally unstable mixtures.

Analysis

The quantitative analysis of sulfur has been based on the colour generated by sulfur when it dissolves in piperidine. Sulfur concentration up to 0.85 mg cm^{-3} could be measured using a 440 nm filter. Any sample having a greater concentration required dilution with piperidine before measurements could be made.

A stock solution of sulfur in piperidine was prepared by dissolving 50.51 mg of sulfur and making the solution up to 50 cm^3 in a volumetric flask. A series of 500 µL aliquots of the stock solution and piperidine were used to prepare a series of solutions containing a range of concentrations of sulfur from 0–0.85 mg cm^{-3}. Approximately 2.5 cm^3 of piperidine was transferred to a 1 cm^3 path glass cuvette and used as the reference solution. About 2.5 cm^3 of prepared solution was placed into a clean rinsed cuvette, the clear surfaces wiped with tissue and an absorbance measurement taken. The procedure was repeated for the series of prepared solutions and the results were used to prepare a calibration curve and spreadsheet model.

A standardised method of extracting sulfur from prepared samples and firework compositions was developed. Consolidated firework compositions were, generally, carefully pared to produce a fine powder to aid dissolution of sulfur. In the case of Black Powder, single grains were very carefully ground in an agate pestle and mortar. Three portions of each sulfur-containing composition were taken and weighed in small sample bottles, 50×18 mm were found suitable. The samples had weights in the range 10–75 mg. A 5 cm^3 aliquot of piperidine was pipetted into each sample bottle which was then stoppered. The samples were left for no more than 10 minutes to allow dissolution of the sulfur, which was aided by gentle shaking of the extract from time to time. After dissolution, the solutions were filtered using tissue- or cotton-plugged dropping pipettes and run into clean sample bottles.

About 0.5 cm^3 of each filtered piperidine solution was used to rinse cuvettes prior to analysis. Then 2–3 cm^3 of the filtered solution was transferred into the rinsed cuvette for absorbance measurement. If the absorbance was on-scale, this value was used directly for calculation. When the solution was too concentrated, it was diluted. To dilute the sample 500 µL aliquots of the filtered piperidine extract were transferred into a clean sample bottle and 500 µL aliquots of piperidine added. The dilution factor required for a particular extract was found by trial and error, but generally 3–4 cm^3 of diluted sulfur extract was produced.

Colorimetry was performed on each of the three extracts to obtain a mean sulfur content of the sample.

It is important that samples are analysed before the yellow colour starts to fade. The colour change was found to be slow. Normally, samples were analysed within 5–10 minutes of extraction.

The quantitative analysis of chlorate has been based on the colour generated by the anion when it reacts with anilinium chloride (aniline hydrochloride). Chlorate solutions with a concentration up to 2 mg cm^{-3} could be measured using a 680 nm filter. If a greater concentration of chlorate was obtained in the primary extraction, dilution of the sample was required.

A stock solution of approximately 0.2% potassium chlorate in water was made by dissolving 0.2003 g of dried potassium chlorate in distilled water and making the solution up to 100 cm^3 in a volumetric flask. A series of solutions containing different concentrations of chlorate in the range 0–2 mg cm^{-3} was prepared by taking 500 µL aliquots of the stock solution and distilled water. A set of 5 cm^3 portions of 5% anilinium chloride (technical grade aniline hydrochloride) in 8M hydrochloric acid were placed into test tubes; 150×20 mm tubes were found suitable. About 4 cm^3 of anilinium hydrochloride solution was placed in a disposable plastic cuvette and used as reference. The colorimeter was set to kinetic mode to measure maximum absorbance from the chlorate-anilinium chloride reaction.

A 500 µL portion of the 0.2% chlorate solution was transferred to a test tube containing 5 cm^3 anilinium chloride solution using an automatic pipette. The solution was rapidly shaken to ensure mixing and about 4 cm^3 transferred into a clean, plastic cuvette. The cuvette was placed in the colorimeter and the absorbance monitored. The maximum absorbance reading was recorded. It was found that the maximum absorbance occurred within 1 minute of mixing. Samples of chlorate which had been diluted were similarly treated using clean disposable plastic cuvettes for each measurement. The results were used to generate a calibration curve and spreadsheet model.

A standardised method for extracting chlorate from prepared samples and firework compositions was developed. Consolidated firework compositions were carefully pared to produce a fine powder to aid dissolution of any chlorate. Careful grinding of single grains could also be undertaken to pulverise any material which did not pare easily. A sample of the composition was taken and weighed in a small sample bottle; 50×18 mm bottles were found suitable. Depending on sample size and chlorate proportion, a 2 cm^3 or 5 cm^3 portion of distilled water, was pipetted into the sample bottle which was then stoppered. The sample was left for up to one hour to allow dissolution of the chlorate, this was aided by gentle shaking of the extract from time to time. The samples had weights in the range 10–50 mg. When the chlorate had dissolved, the solution was filtered into a second sample bottle using a tissue- or cotton-plugged dropping pipette.

The colorimeter was set to kinetics mode and about 4 cm^3 of anilinium chloride solution placed in a clean cuvette to act as a blank. A 500 µL aliquot of the extract was added to 5 cm^3 of anilinium hydrochloride solution. This was shaken and about 4 cm^3 immediately transferred to a clean, disposable plastic cuvette. The cuvette was placed in the colorimeter and the maximum absorbance was measured and recorded. If the solution saturated the colorimeter, the remaining extract was diluted, until "on scale" readings could be obtained by taking 500 µL aliquots of extract and 500 µL aliquots of water. There was sufficient undiluted solution from a 2 cm^3 extract for triplicate analysis by colorimetry.

The reproducibility of the method was established by taking mixtures containing potassium chlorate and sodium chloride. These were prepared by weighing portions of potassium chlorate, adding appropriate amounts of sodium chloride, and re-weighing. The mixtures, about one gram, were produced with approximate potassium chlorate proportions of 10, 20 and 50%. The mixtures were shaken for 5–10 minutes to attain an even distribution of the components.

Appropriately sized samples were weighed into a series of sample bottles and 2 cm^3 (10% sample) or 5 cm^3 (20% and 50% samples) of distilled water added to produce a solution with concentration "on scale" for measurement. After allowing 10–15 minutes for dissolution, the samples were analysed by the standard procedure.

Errors in Measurement

The errors in measurement are dominated by the colorimeter measuring a scale of 0–2 to the nearest 0.01 in the absorbance scale. This introduces a limit to the accuracy of calculation of the percentage sulfur or chlorate in a composition. Additionally, the accuracy varied depending on the sample size taken to attain an on-scale reading (either as a direct limit on the sample size or through dilution). At about 5% sulfur content the colorimeter step size is under 0.1 while at 30% the step size rises to about 0.3. Similar effects were seen with the chlorate analysis where the colorimeter step size was increased to 0.4 at 50% chlorate in a sample.

Results

A set of six dilutions of sulfur in piperidine were prepared and the absorbances measured to produce the calibration graph, shown as Figure 1. The best fit regression line through the origin was generated. This line gave a correlation coefficient (R^2) value of >0.99 indicating a "good fit".

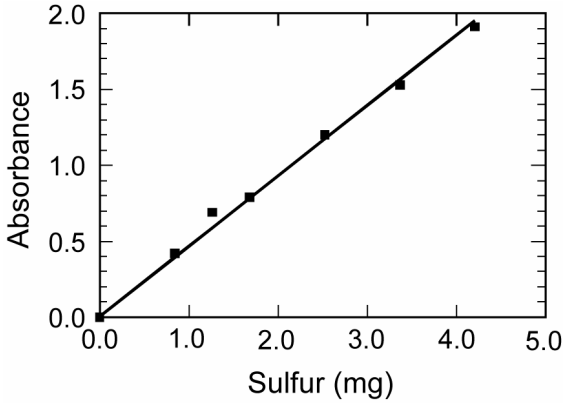

Figure 1. Sulfur calibration.

Reproducibility of the analysis for sulfur was examined using mixtures of sulfur in talc with approximately 5, 16 and 27% sulfur. The samples were analysed by the standard procedure and the results are reported in Table 1.

Table 1. Reproducibility of Sulfur Analysis.

Calculated % sulfur for 5.1% sample	Calculated % sulfur for 16.3% sample	Calculated % sulfur for 27.1% sample
4.9	15.3	27.6
5.1	15.2	27.0
5.0	16.0	27.1
5.0	16.9	26.6
5.1	16.1	27.9
5.3	15.3	27.1
4.7	16.0	26.8
4.8	24.0	28.1
4.9	16.3	28.1
5.0	15.1	27.0
Mean 5.0	Mean 16.6	Mean 27.3
Std. Dev. 0.2	Std. Dev. 2.7	Std. Dev. 0.6

Firework components were analysed and gave mean calculated sulfur contents of 3–30%, this is reported in Table 2.

Table 2. Sulfur Analysis, Firework Samples.

Sample	Extract	Calculated % sulfur	Mean (%)	Std. Dev.
Lift charge	A	9.5	10.2	1.0%
	B	11.0		
	C	10.9		
Flash composition	A	30.1	29.2	0.8%
	B	28.9		
	C	28.6		
Star outer composition	A	8.1	7.8	1.2%
	B	6.5		
	C	8.8		
Star inner composition	A	3.0	2.9	0.1%
	B	2.8		
	C	3.0		

In this study the amount of chlorate was calculated as the percentage of potassium chlorate, the most commonly used chlorate in fireworks. No tests have been performed on firework compositions to ascertain the presence of other chlorates.

A set of five dilutions was prepared and duplicate pairs of results used to generate the calibration graph shown in Figure 2. The best fit regression line through the origin was generated. This line gave a correlation coefficient (R^2) of >0.98 indicating a "good fit".

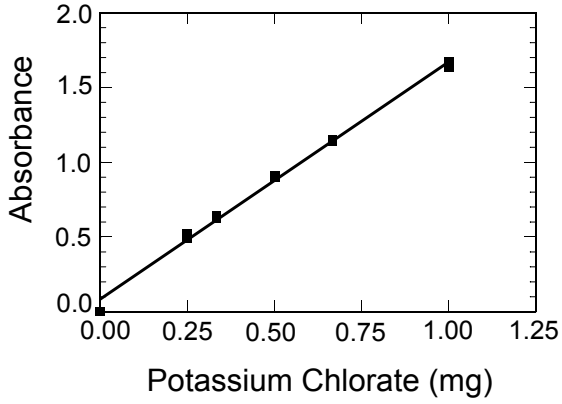

Figure 2. Chlorate calibration.

A series of three samples was prepared for the reproducibility testing. The samples contained 9.15, 19.7 and 50.2% potassium chlorate. The results of five sets of duplicate analysis are shown in Table 3. The levels of potassium chlorate derived from absorbance readings were found, within experimental error, to be in good agreement with the concentrations present in the dried samples. Additionally, as the proportion of potassium chlorate increased, there was a corresponding increase in the standard deviation. This is because, as the potassium chlorate proportion increases, a 0.01 change in absorbance registered on the colorimeter gave an increasing change in the potassium chlorate content.

Firework compositions containing chlorate were analysed following the standardised extraction procedure. Tests were carried out on firework composition without any drying. This was likely to underestimate the amount of chlorate, due to moisture uptake. Table 4 lists example firework compositions and their chlorate content. Chinese flash-banger composition, Flash composition in Table 4, was found to contain the highest proportion of chlorate, measured as potassium chlorate, at 46.2%.

Table 3. Reproducibility of Chlorate Analysis.

Calc. $KClO_3$ for 9.15% sample (%)	Calc. $KClO_3$ for 19.7% sample (%)	Calc. $KClO_3$ for 50.2% sample (%)
9.4	18.3	51.4
9.4	18.0	49.9
9.1	20.9	48.8
9.0	20.0	48.2
9.1	19.3	50.3
9.1	19.3	50.3
9.2	20.4	49.9
9.3	20.4	50.2
9.7	20.9	51.9
9.6	20.6	52.7
Mean 9.3	Mean 19.8	Mean 50.4
Std. Dev. 0.2	Std. Dev. 1.0	Std. Dev. 1.3

Table 4. Chlorate Analysis of Firework Compositions.

Sample	Extract	Calculated % $KClO_3$	Mean	Std. Dev.
Flash composition	A	46.1	46.2	0.2
	B	46.4		
	C	46.1		
Fuse composition	A	12.0	12.4	0.3
	B	12.6		
	C	12.5		
Star outer composition	A	11.4	11.2	0.2
	B	11.0		
	C	11.2		
Star inner composition	A	2.6	3.1	0.5
	B	3.4		
	C	3.4		

Discussion

Sulfur-containing samples for the reproducibility study were individually weighed from the solid mixture. It was anticipated that there could be variation in the sulfur levels found due to incomplete homogeneity. The 5.1% sulfur-containing sample give a mean value of 5.0% sulfur with a standard deviation of 0.2%. Problems with homogeneity were

encountered with the 16.3% sulfur-containing mixture, since the mean calculated sulfur content of 16.6% was achieved with six values below the sulfur percentage, three just over and a single value very much higher at 24.0%. This latter value was outside two standard deviations of the mean. The mixture for the third series of samples was ground in an agate pestle and mortar to ensure that any agglomeration of the sulfur was broken down and the material evenly mixed. The resulting calculated value of 27.3% was within experimental error (compared with the sample prepared at 27.1%) with no exceptionally high or low values. The standard deviation from the results was 0.6%

The extraction of sulfur from fireworks compositions depends on the state of the sample. Star compositions, for example, are consolidated into a hard solid mass, often with multiple layers. Initial separation of the layers may lead to contamination if the operator is not very careful. Once the material has been separated the sample will contain a mixture of fine and coarse particles. In practice, it is likely that all the material will be required for analysis. In the current study, star outer compositions yielded 10–15 mg of material for analysis from each star. For sulfur analysis this required one star per analysis. Thus there was the added possibility of some variation in composition between stars. For most compositions it was possible to obtain sufficient material to extract from fine particles. Re-extraction produced only the slightest trace of colour, indicating good primary extraction.

Lift charges in fireworks are often Black Powder. Lancaster[5] has reported that the usual composition for Black Powder contains 10% sulfur. Analysis of roman candle lift charges showed these to contain 10.2% sulfur. At this sulfur proportion the method is accurate to about 0.1%. A standard deviation of 1.0% is attributed to variation of composition within the samples. No investigation of the absorption of sulfur into charcoal during the extraction has been made. This could, in part, contribute to the variation in results.

Flash-banger composition may well contain sulfur. Weingart[6] reports one such composition for a "flash cracker" as having 30% sulfur by mass. The flash composition tested in this program of work was found to have 29.2% sulfur. At this level a 0.01 change in absorbance results in a 0.2–0.3% change in estimated sulfur content.

Star compositions have also been found to contain sulfur. This is often incorporated to ease ignition.[7] The star inner composition analysed was found to contain 2.9% sulfur with a standard deviation of 0.1%. The outer priming composition contained about 8% sulfur with a standard deviation of 1.2% over the three extracts. Each star outer composition was pared from the inner composition and yielded only sufficient material for a single extraction. Thus each measurement represents the outer material from a different star. It is possible that star B outer contained a larger proportion of large particles from the paring, or was of a different composition. As the three stars had all originated from the same roman candle, it was thought that sample B had larger particles and was therefore not completely extracted in the time allowed before filtering and measuring the absorbance.

Chlorate analysis was performed by colorimetry. The method adopted was developed from the oxidiser test described in the British Standard. This spot test uses the blue colour produced by anilinium chloride in the presence of certain oxidisers. Common oxidisers found in fireworks are chlorates, nitrates and perchlorates. Of these only chlorate oxidises anilinium chloride in 8M hydrochloric acid. Other oxidisers that oxidise anilinium chloride and could interfere with the test are: permanganate, chromate and dichromate, peroxide and some other peroxy-salts.

Additional complication in the colorimetric method resulted from the kinetics of the reaction. In a typical analysis the blue colour developed over about one minute from addition of the chlorate solution and then slowly faded to a pale green. With vigorous mixing of the reagent and test solution and rapid transfer into a cuvette the maximum absorbance was found to be directly proportional to the concentration of chlorate in the test sample.

Firework samples were screened by using the chlorate identification test (i.e., an anilin-

ium chloride spot test followed by the confirmatory testing for halide, reducing the chlorate with sodium nitrite solution and retesting for halide). Due to the use of the oxidiser test as a basis for quantitative analysis it was felt necessary to always confirm the presence of chlorate before quantitative analysis was performed.

The reproducibility of the method was investigated with three mixtures containing 9.15, 19.7 and 50.2% potassium chlorate in sodium chloride. Mean potassium chlorate levels were measured and were within experimental error. As the concentration of chlorate increased the standard deviation also increased. This was attributed to the effect of the colorimeter step size since the absorbance is measured to two decimal places. The effect of this is a step size of 0.1 at 9.15% chlorate, 0.2 at 19.7% chlorate and 0.4 at 50.2% chlorate, for a 0.01 change in absorbance.

Flash-banger compositions used in fireworks normally contain chlorate or perchlorate with a fine metal powder, typically aluminium.[8] Chinese firecracker composition is reported by Conkling[9] to be a mixture of potassium chlorate, sulfur and aluminium. One such composition, described as Japanese "flash thunder" has potassium chlorate as 43% by mass. The flash composition tested had a potassium chlorate content of 46.2%.

Star compositions require the presence of chlorine in one of its oxidation states to form the coloured species SrCl or BaCl which generate red and green colours. Lancaster[10] reports both red and green stars to contain high proportions of chlorate in the composition. The Roman candle stars tested in the course of this work indicated 3.1% chlorate in the main star and 11.2% in the priming composition surrounding the body of the star. These stars had been declared as using perchlorate as oxidiser and chlorate should not have been present.

During check examination of fireworks, fuses were found to be the most common location for sulfur/chlorate admixtures. Analysis showed there to be 12.4% chlorate in what appeared to be a typical Bickford type fuse. It could be anticipated that this would be variable from batch to batch.

Conclusions

Previous examinations of fireworks for sulfur/chlorate admixtures have concentrated on identifying only the presence of these chemicals, not the amount. This was because of the absence of a quick and reliable quantitative method such as is presented in this paper. The development of a technique that can be used as a routine part of any sampling and testing campaign will enhance enforcement of the relevant legislation.

Routine quantitative analysis of firework compositions has not previously been available. The methods described in this paper should enable the levels of both sulfur and potassium chlorate in a firework composition to be assessed and distinctions to be made between different admixtures. Future work on the stability and reactivity of these admixtures may enable acceptable potential hazards to be estimated.

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10) Ref. 5, p 87.

Errata — Issue No. 4

Page 26: The value for aluminum in the table is incorrect. The corrected table follows:

Table 1. Oxidation of Metal Fuels by Air.

Fuel	Grams Oxidized by 299 g Oxygen (1 m^3)*
Aluminum	336
Titanium	449
Magnesium	445
Zirconium	852

* Reactions with nitrogen will be ignored.

Page 31: The value for the burst charge weight for Test 13 was 16 g, not 24 g as listed in the table.

Page 45: The first line on the page was inadvertently dropped when it was printed. The missing text is:

"The variation in pressure which they produce"

A Survey of Concussion Powders

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ABSTRACT

A collection of six commercial concussion powders were test fired in concussion mortars to determine internal mortar pressures, air blast pressures, and the durations of air blast positive phase. The internal mortar pressures for various powder types and load mass ranged from less than 200 psi (1.4 MPa) to nearly 100,000 psi (700 MPa). For the same powder loads, the air blast pressures at a distance of approximately 70 inches (1.8 m), ranged from 0.07 psi (0.5 kPa) to 1.7 psi (12 kPa). This corresponds to sound pressure levels (peak–ultra fast–linear) ranging from 148 dB to 175 dB, and relative loudness values ranging from 1.0 to 6.8. For the same powder loads, the durations of positive phase ranged from nearly 4 ms down to 0.7 ms.

Keywords: concussion powder, blast wave, mortar pressure, sound pressure level, loudness

Introduction

In an earlier article,[1] the results of a fairly detailed study of one commercial concussion powder (Pyropak®) were reported. The present article reports on a study of a collection of concussion powders from various manufacturers. Since it was not practical to repeat the full study for each of the other concussion powders, it was decided to compare the performance of the powders at only a few selected load masses. All suppliers of concussion powder known to the authors were contacted; all but one agreed to participate in the study, and provided samples of their powders.

Since beginning this study, the catastrophic failure of a concussion mortar (without injury) has been reported.[2] This increased both the interest and the relevance of this study, and provided the impetus for an early release of some of the results.[3] The present article is a more thorough presentation and discussion of those results.

It should be noted that the purpose of this study was to measure the performance characteristics of the concussion powders. The purpose was not to rate the performance of the concussion powders. To rank the concussion powders, it would first be necessary to establish a set of evaluation criteria; however, those criteria are likely to be quite different for various users with different applications. Hopefully, this study provides basic information which both users and manufacturers will find useful, or at least interesting.

Background

In its most common form, a concussion mortar consists of a thick, cylindrical steel bar, welded to a heavy base plate. The mortar contains a combustion chamber (barrel), produced by drilling a hole on-axis into the top end of the steel bar. The mortar used in this study was 2 inches (5 cm) in outer diameter, with a 1 inch (2.5 cm) hole drilled to a depth of 4.5 inches (11.5 cm). The construction of the mortar is illustrated in Figure 1, which also shows it loaded with a charge of powder and an electric match for ignition.

Upon ignition, because of the confinement provided within the combustion chamber, the concussion powder deflagrates (burns explosively), see Figure 2. The high internal pressure causes the combustion products (gases and solid particles) to be accelerated outward. As the gases exit the end (mouth) of the mortar, they expand to produce a shock wave that is heard and felt by the audience. As a result of the ejection of combustion products, a downward recoil force is produced. In a previous study, it was

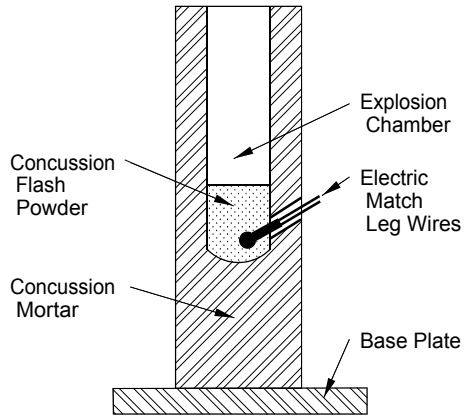

Figure 1. An illustration of the construction and setup of a concussion mortar.

demonstrated that the shape of the recoil force curve follows the shape of the internal pressure curve.[1a] Further, it was demonstrated that the magnitude of the recoil force depended on the rigidity of the surface under the mortar. Accordingly, the value of collecting recoil data is diminished and that data was not generated in this study.

Figure 3 illustrates a typical blast overpressure profile. Before the arrival of the blast wave at the pressure sensor, there is no indication (with respect to pressure) that an explosion has taken place or that the blast wave is approaching. When the leading edge of the blast shock wave arrives, it produces an essentially instantaneous rise in pressure from ambient to some maximum value. Thereafter, the pressure decays much more gradually back to ambient pressure. This portion of the blast wave is referred to as the positive phase. Following the positive phase, there is a negative phase, during which pressure drops below ambient. In essence, this is caused by over expansion of the gases, wherein the outward rush of air continues beyond that necessary to relieve the pressure produced by the explosion. Thus, a partial vacuum forms at the seat of the explosion, producing the negative phase of the blast wave. It is less extreme than the positive phase and lasts longer.

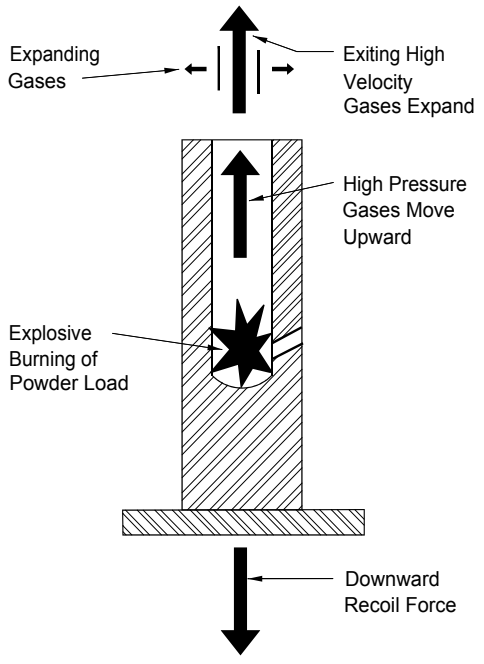

Figure 2. An illustration of the firing of a concussion mortar.

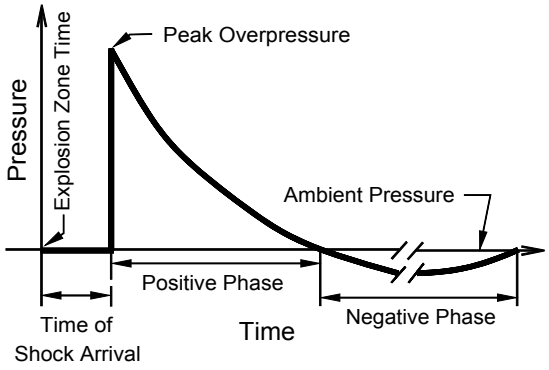

Figure 3. An illustration of a typical overpressure profile (blast wave) produced by an explosion.

Sound pressure level (*SPL*, in decibels, dB) is a physically measurable quantity and can be calculated from blast overpressure measurements using the relationship shown in equation 1.[4,5][a] Using the recognized standard reference level of 0.0002 dyn/cm^2, this becomes equation 2. As can be seen, there is a logarithmic relationship between sound pressure levels and peak overpressure (P).

$$\mathrm{SPL} = 20 \bullet \log \frac{P}{P_o} \qquad (1)$$

$$\mathrm{SPL} = 170.8 + 20 \log P \qquad (2)$$

where P_o is the standard reference value of 0.0002 dyn/cm^2.

Loudness is a subjective measure of sound level, dependent on the processing of nerve impulses by the brain. The loudness scale is linear, such that a sound with a loudness value twice that of another sound will be perceived by a typical listener to be twice as loud. Loudness values (N, in phons) can be calculated from sound pressure levels using the relationship shown in equation 3.[5] However, because loudness expressed in phons is not a unit of measure with which many readers are accustomed, in this article, loudness is reported as relative loudness. The least loud average concussion mortar air blast was assigned a value of 1.0. Thus a concussion mortar blast reported as producing sound with a relative loudness of 2.0 or 5.0 will be perceived by the average listener to be two or five times as loud, respectively.

$$\log N = 0.03 \bullet \mathrm{SPL} - 1.2 \quad (3)$$

$$N = 10^{(0.03 \bullet \mathrm{SPL} - 1.2)} \quad (4)$$

In addition to the loudness of a concussion mortar blast, the tonal quality of the sound may also be of interest. That is to say, does the sound produced tend toward being a sharp crack or a more mellow boom? The feature of a blast wave that is conjectured to correlate with perceived tonal quality is the duration of the positive and negative phases. All else being equal, shorter phase durations are expected to be heard more nearly as sharp cracks, and longer phases as more mellow booms. There are at least two reasons for being somewhat cautious about proclaiming that tonal quality correlates with phase duration. First is that tonal quality is a subjective (mental) response to a physical stimulus (the blast pressure wave), and the brain may not process this information as one might expect that it should. Second is that the authors are not aware of any comprehensive study of perceived tonal quality as functions of blast wave phase duration.

It is also conjectured that the rate of rise of the leading edge of the positive phase (dP/dt) may affect tonal quality. It is expected that sharper rises will be perceived as being sharper sounding. However, at the short distance at which measurements of the blast waves were made in this study, all had a near instantaneous rise.

While on the subject of tonal quality of blast waves, it is appropriate to mention that the subject is made more complicated because a complex relationship has been demonstrated between perceived loudness and tonal quality for pure tones.[6] Further, the results for a brief study of spectator responses to the sounds produced by fireworks salutes, suggests a strong correlation between loudness and tonal quality, which, however, is in the opposite direction as that reported for pure tones.[6,7] Accordingly, for the purpose of this article, it will only be assumed that tonal quality correlates with phase duration, at least for equally loud sounds.

Experimental Method[b]

Table 1 lists information regarding the binary concussion powders (so-called A–B mixes) used in this study. The powders are listed in order of the internal mortar pressures they produced, from the lowest to highest pressure. Most of the information in the table was gathered from Material Safety Data Sheets and user instructions provided by the manufacturers. One exception is the fuel to oxidizer ratios that were obtained by simply weighing the contents of the containers for the two components and rounding to the nearest 5%. Not included in Table 1 is information about particle size of the components; it was felt this would be proprietary information of the manufacturers. It should also be noted that some of these samples were provided approximately two years ago; thus it is possible that the manufacturers may have made changes in their formulations which are not reflected in this study. Further, Astro Pyrotechnics has recently announced that they are discontinuing the general sale of their concussion powder.

Table 1. Concussion Powder Information.

Supplier and *Product Name*	Fuel (a)	Oxidizer (a)	Fuel:Oxidizer Ratio (b)	Loading Instructions (c)
Luna Tech (Pyropak®) *Concussion Flash powder*	Magnesium	Strontium Nitrate	50:50	1 oz. (28 g) (maximum)
Newco Products *Fast Theatrical Flash Powder*	Magnesium	Potassium Perchlorate	70:30	14 g (1/2 oz.) (maximum)
MP Associates *Super Flash Powder*	Magnesium	Potassium Perchlorate	60:40	Not Specified
Astro Pyrotechnics *Sound Flash Powder*	Magnesium	Potassium Perchlorate	50:50	1 capful (d)
Theatre Effects *Sonic Chemical*	Aluminum	Potassium Perchlorate	30:70	1/4 tsp.(e) (typical) (f)
Precision Theatrical *Concussion*	Aluminum	Potassium Perchlorate	30:70	(g)

(a) As specified on manufacturer's Material Safety Data Sheet.

(b) Determined by weighing the contents of a single pair of bottles supplied for testing. The ratios are rounded to the nearest 5%.

(c) As specified in the manufacturer's instructions supplied with the product.

(d) One capful is approximately 2.7 grams.

(e) One teaspoonful is approximately 1.7 grams and one heaping teaspoon is approximately 2.5 grams.

(f) There is the additional instruction, "Increase ... slightly if ... not loud enough."

(g) The supplier reports that the powder is supplied with a recommendation to use a mortar with a 1 inch (2.5 cm) wall thickness.

The test concussion mortar had been modified, as shown in Figure 4, to allow attachment of a quartz piezoelectric pressure transducer for recording internal pressure during its firing. Unfortunately, in retrospect, this was not the ideal configuration. The length of passage to the pressure gauge should have been shorter and more importantly it should not have had a 90º bend. Nonetheless, this is the configuration that was available and that was used. The overall results of this comparative study should have not been significantly affected by using this configuration.

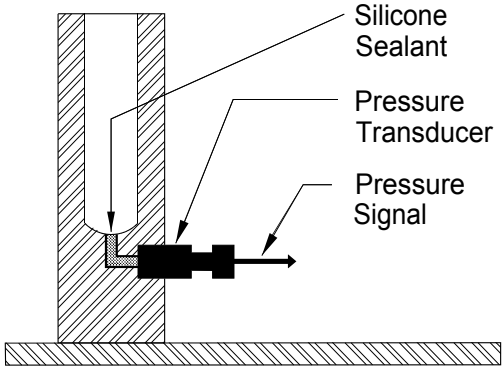

Figure 4. An illustration showing the installation of the pressure transducer.

The pressure gauge was a PCB Piezotronics (Model 109A02) calibrated to 120,000 psi (830 MPa). To protect the gauge and to keep concussion powder out of the passageway from the

combustion chamber to the pressure transducer, that space was filled with an opaque silicone sealant (Permatex, High Temp RTV, #26B). The sealant was allowed to cure for at least a week before use. Occasionally during the testing of concussion powders producing the highest internal pressures, the silicone sealant loosened and was eroded. On those occasions, the sealant was removed, replaced and allowed to cure before testing continued.

When measuring pressures below approximately 2000 psi (14 MPa), the silicone sealant acts to attenuate the pressure sensed by the gauge. (Presumably this related to having a long path with a 90º bend between the chamber and the gauge). To develop a pressure correction curve, a series of twenty four firings were performed using various amounts of Pyropak concussion powder. These results were compared with data collected previously[1b] in which the passageway had been filled with a light weight silicone grease. The correction factors produced are the average ratio of the values obtained with and without the sealant. These values were plotted in Figure 5 and a smooth curve drawn through the data points.

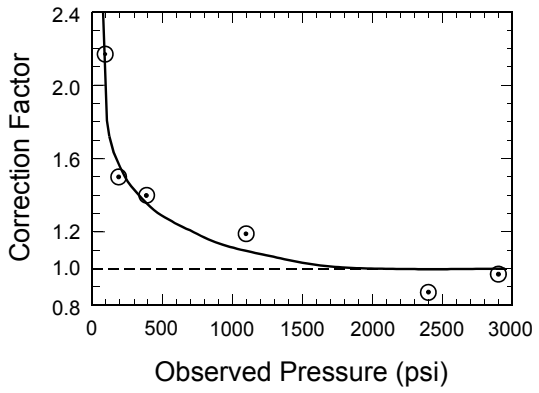

Figure 5. Graph of factors used to correct mortar pressures for the presence of silicone sealant.

Air blast overpressures were measured using a PCB Piezotronics free field blast gauge (Model 137A12), setup as shown in Figure 6. This geometry was chosen to duplicate that used in an earlier study,[1] which had been chosen for convenience and because it seemed a reasonable choice. The pressure sensor was shielded from thermal radiation by a thin film of silicon grease that was covered tightly with a 0.001 inch (0.025 mm) film of aluminized mylar.

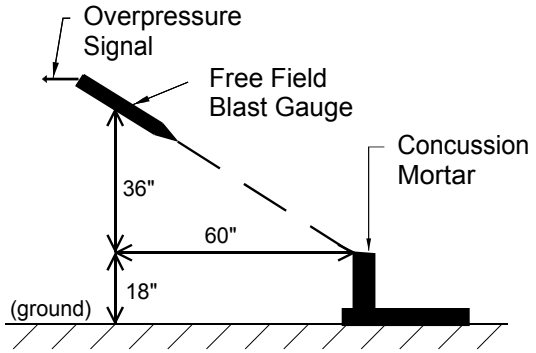

Figure 6. An illustration of the physical setup used to collect concussion mortar air blast overpressures. (For conversion of units, 1 inch=25.4 mm)

The electric matches used to ignite the concussion powders in this study were Daveyfire SA-2000. The electric matches were installed near the bottom of the powder charge (see Figure 1). The procedure was to insert the match until it touched the bottom of the mortar, and then it was withdrawn approximately 1/8 inch (3 mm). Over the course of these and earlier tests, the diameter of the electric match hole in the mortar had eroded quite large, to an irregular diameter of approximately 0.25 inch (0.5 cm). In addition, repeated prior use of the mortar had also eroded the bore of the combustion chamber to approximately 1.05 inches (2.7 cm). It is likely these erosions caused the measured internal mortar pressures to be less than might otherwise have been the case.

Output from both PCB transducers (internal mortar pressure and blast overpressure) were fed to amplifying power supplies (PCB Model 480D09), and recorded using digital oscilloscopes. Permanent storage and plotting of the data was accomplished using a computer.

Typically each concussion powder was tested with loads of 7, 14, 21, and 28 grams. However, when any concussion powder load mass produced an internal pressure that approached

100,000 psi (700 MPa) for any individual firing, or if a series of firings produced pressures that averaged more than 30,000 psi (200 Mpa), no greater loads were tested. When these values were exceeded for light powder loads, additional tests with various low mass loadings were performed.

Results

In this section, the results of the test firings are reported without comment. (The discussion of the results is deferred until the next section.) The results from the individual firings are reported in Tables 2 through 7. Typically there were three test firings for each load mass with each powder. However, in some cases additional firings were conducted. Sometimes this was because of a failure to successfully capture both types of pressure data for reasons such as data being off-scale. Other times this was the result of some initial testing being performed in a test chamber in which it was felt that there was insufficient space above the concussion mortar to collect reliable air blast data. [This was only a problem for those concussion powders with formulations that were particularly fuel rich (i.e., Pyropak's and Newco's.)] This is discussed further in the next section.

In Tables 2 through 7, the column headed "Pres." presents the data from internal mortar pressure measurements. The column "FWHM" is an abbreviation for Full Width at Half Maximum. This is simply the width of the internal pressure peak, measured at one half of its peak value. It is an indication of the width of the pressure peaks. When the pressure curves have

Table 2. Results of Measurements Using Luna Tech/Pyropak's "Concussion Flash Powder".

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
7	190	7.4	1.4	0.07	4.4	0.11
7	180	7.8	1.1	0.08	3.4	0.11
7	180	8.8	1.2	0.05	3.4	0.08
14	1000	2.0	2.0	—	—	—
14	1600	2.3	4.3	—	—	—
14	630	4.6	2.9	0.21	4.1	0.33
14	1200	2.3	3.1	0.21	3.8	0.46
14	1500	1.9	3.1	0.46	2.9	0.64
21	3500	1.8	6.4	—	—	—
21	2700	2.4	6.3	—	—	—
21	2800	1.6	4.4	0.88	2.1	0.75
21	1600	2.0	3.3	0.87	2.1	0.86
21	1300	1.8	2.3	0.72	2.1	0.81
28	3300	2.2	7.3	—	—	—
28	4000	1.7	7.5	—	—	—
28	2700	2.2	4.9	1.1	2.1	0.99
28	2400	1.9	4.7	1.3	2.3	1.1
28	2300	1.9	4.6	1.5	1.5	1.0

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

Table 3. Results of Measurements Using Newco Products' "Fast Theatrical Flash Powder".

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
7	1400	1.2	1.7	0.55	2.2	0.48
7	1500	1.0	1.6	0.56	1.5	0.55
7	1400	1.2	1.7	0.58	1.1	0.52
7	—	—	—	0.48	2.1	0.39
14	2800	1.3	3.5	—	—	—
14	2800	1.3	3.3	—	—	—
14	4800	0.84	3.6	—	—	—
14	2600	1.5	3.7	1.0	1.5	0.70
14	3100	1.2	3.7	1.3	1.5	0.68
14	2800	1.4	3.6	1.0	1.3	0.71
21	3200	1.4	4.4	1.6	1.3	0.85
21	4900	1.2	5.7	1.6	1.3	0.88
21	3600	1.8	5.7	1.5	1.6	0.93
28	5100	1.3	6.9	1.8	1.3	0.99
28	5800	1.1	7.1	1.9	1.3	1.1
28	4400	1.7	6.8	1.6	1.3	1.1

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

Table 4. Results of Measurements Using MP Associates' "Super Flash Powder".

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
7	1600	1.4	2.0	0.54	1.8	0.44
7	1700	1.2	2.1	0.81	1.5	0.44
7	1700	1.2	2.1	0.71	1.4	0.45
14	7800	0.50	4.0	1.4	1.2	0.71
14	5700	0.70	3.7	1.5	1.1	0.75
14	5600	0.58	3.7	1.5	1.1	0.75
21	12000	0.48	5.8	1.9	1.2	0.94
21	9900	0.56	5.6	2.0	1.1	0.96
21	13000	0.42	5.6	1.8	1.1	0.96
28	16000	0.30	6.3	2.3	0.94	1.1
28	6700	1.0	7.1	2.1	1.0	1.1
28	15000	0.12	6.5	2.0	0.96	1.1

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

Table 5. Results of Measurements Using Astro Pyrotechnics' "Sound Flash Powder."

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi · s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi · ms)
7	3400	0.56	1.9	1.2	0.92	0.40
7	3600	0.58	2.0	1.2	0.76	0.39
7	3600	0.52	1.9	1.2	0.84	0.41
14	6600	0.51	3.0	1.9	0.86	0.79
14	18000	0.12	3.9	1.6	0.84	0.63
14	7400	0.44	3.8	1.7	0.83	0.61
21	34000	0.14	4.4	2.1	0.87	0.87
21	12000	0.31	4.4	2.1	0.88	0.86
21	47000	0.17	4.3	2.1	0.87	0.87

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

Table 6. Results of Measurements Using Theatre Effects' "Sonic Chemical" Powder.

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi · s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi · ms)
3	3700	0.16	0.89	1.0	0.58	0.21
3	1900	0.30	0.71	0.81	0.47	0.19
3	2100	0.27	0.72	0.78	0.58	0.20
5	4100	0.24	1.2	1.1	0.60	0.32
5	4400	0.22	1.3	1.2	0.65	0.34
5	4500	0.22	1.3	1.2	0.65	0.34
7	5600	0.25	1.8	1.3	0.70	0.43
7	3700	0.21	1.9	1.4	0.70	0.43
7	18000	0.04	2.0	1.3	0.71	0.43
9	18000	0.10	1.9	1.5	0.78	0.52
9	13000	0.12	2.1	1.7	0.78	0.57
9	19000	0.11	2.3	1.7	0.78	0.60
11	44000	0.03	2.6	1.6	0.79	0.61
11	—	—	—	1.7	0.80	0.65
11	92000	0.05	4.6	1.7	0.81	0.66

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

a simple shape (see Figure 7B in the next section), FWHM is a good indicator of relative peak width. However, when the pressure peaks have an irregular or complex shape (see the other curves of Figure 7) this is a less reliable indicator, but it is still somewhat useful. The column titled "P. Imp." presents pressure impulse data, the area under the internal mortar pressure versus time curves. The column headed "Blast" reports peak air blast overpressure results. The column titled "Pos. Ph." presents the duration of the positive phase portion of the air blast wave. Finally, the column headed "B. Imp." presents the blast impulse, the area under the positive phase portion of the air blast overpressure curve.

Table 7. Results of Measurements Using Precision Theatrical's "Concussion" Powder.

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
2	1300	0.28	0.32	0.62	0.56	0.18
2	4000	0.10	0.38	0.81	0.50	0.21
2	1400	0.20	0.33	0.70	0.50	0.20
2	2000	0.15	0.34	0.77	0.50	0.21
3	5400	0.10	0.61	1.0	0.58	0.27
3	4900	0.11	0.58	1.0	0.60	0.27
3	6300	0.11	0.58	1.1	0.66	0.27
4	9400	0.10	0.91	1.1	0.60	0.33
4	9900	0.07	0.88	1.2	0.60	0.33
4	8000	0.08	0.90	1.4	0.63	0.35
5	9500	0.12	1.2	1.4	0.62	0.39
5	19000	0.09	1.2	1.5	0.68	0.43
5	5000	0.19	1.0	1.4	0.63	0.40
6	6000	0.18	1.2	1.3	0.70	0.42
6	11000	0.10	1.2	1.4	0.74	0.44
6	7200	0.17	1.2	1.2	0.71	0.40
7	11000	0.12	1.7	1.4	0.74	0.47
7	17000	0.08	1.5	1.3	0.74	0.46
7	19000	0.06	1.8	1.3	0.74	0.47
9	14000	0.15	2.1	1.4	0.77	0.52
9	15000	0.09	2.1	1.4	0.77	0.52
9	86000	0.02	3.1	1.5	0.77	0.55

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

At the end of this section, Table 8 presents averages for the test results from Tables 2 through 7. In addition, average sound pressure levels and relative loudness values are reported in the columns titled "SPL" and "Rel. Loud.", respectively. These were calculated from the peak overpressure data using equations 1 and 2.

In Table 8, because of the small number of test firings for each load mass, and because of the large variations observed in the individual results, it was felt to be inappropriate to report standard deviations. One reason for including the results from individual test firings (Tables 2 through 7) is that a simple inspection can provide a rough estimate of the variability of the results. Note that relatively little of the variability is thought to be the result of the measurement process, but rather it is from actual differences in the combustion processes from test to test. A consequence of the significant variability of the results is that they are only reported to two significant figures.

Table 8. Average Results for the Various Sources of Concussion Powder.

Powder Load (g)(a)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)	SPL (dB)	Rel. Loud.
LP 7	180	8.0	1.2	0.07	3.7	0.10	148	≡1.0
LP 14	1200	2.6	3.1	0.29	3.6	0.47	160	2.3
LP 21	2500	1.9	4.7	0.82	2.1	0.81	169	4.4
LP 28	2900	2.0	5.8	1.3	2.0	1.0	173	5.8
N 7	1400	1.1	1.7	0.54	1.7	0.48	165	3.4
N 14	3300	1.3	3.6	1.1	1.4	0.70	172	5.2
N 21	3900	1.5	5.3	1.6	1.4	0.89	175	6.5
N 28	5100	1.4	6.9	1.8	1.3	1.1	176	7.0
MP 7	1700	1.3	2.1	0.69	1.6	0.44	168	4.0
MP 14	6400	0.59	3.8	1.5	1.1	0.74	174	6.3
MP 21	12000	0.49	5.6	1.9	1.1	0.95	176	7.3
MP 28	13000	0.47	6.6	2.1	0.97	1.1	177	7.7
A 7	3500	0.55	1.9	1.2	0.84	0.40	172	5.5
A 14	11000	0.36	3.6	1.7	0.84	0.68	175	6.8
A 21	31000	0.17	4.3	2.1	0.87	0.87	177	7.7
A 28	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
TE 3	2600	0.24	0.77	0.86	0.54	0.20	170	4.5
TE 5	4300	0.23	1.3	1.2	0.63	0.33	172	5.5
TE 7	10000	0.17	1.9	1.3	0.70	0.43	173	5.7
TE 9	17000	0.11	2.1	1.6	0.78	0.56	175	6.5
TE 11	68000	0.04	3.6	1.7	0.80	0.64	175	6.8
TE 13	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
PT 3	5500	0.11	0.59	1.0	0.61	0.27	171	4.9
PT 5	11000	0.13	1.1	1.4	0.64	0.41	174	6.0
PT 7	16000	0.09	1.7	1.3	0.74	0.47	173	5.7
PT 9	38000	0.09	2.4	1.4	0.77	0.53	174	6.0
PT 11	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

(a) LP = Luna Tech/Pyropak; N = Newco Products; MP = MP Associates; A = Astro Pyrotechnics; TE = Theatre Effects; PT = Precision Theatrical.

(b) Pressure limit criterion was exceeded for the next lower load mass, no test was performed for this load mass.

Discussion of Results

For test firings of the most fuel-rich concussion powders, it was found that credible data could not be collected in a blast chamber with only an 8-foot (2.4 m) ceiling. The air blast peak shapes observed were seriously distorted compared with those collected in a larger chamber and for less fuel-rich powders. This observation may be consistent with the most fuel-rich powders producing a portion of their blast wave from a fuel-air explosion above the mortars.

In this study, as in an earlier study,[1] a large degree of variability was observed for internal mortar pressure pulse shapes. Examples of these shapes are shown in Figure 7. It is likely that the peak shapes are real and reflect differences in the combustion process. This is because the type of pressure pulse shape observed tends to be predictable, based on load mass and powder type. Further, it has not been possible to postulate a simple model for how a problem with the

instrumentation could produce such widely varying shapes with consistent pressure impulses (peak areas). Another reason to believe the various peak shapes are real is the recoil forces, measured independently in the earlier study, tended to mirror the internal pressure peaks.[1c]

The curve in Figure 7A is typical of that observed for light loads of the low pressure Pyropak powder. There is a cluster of peaks spanning about 12 ms, with a maximum pressure of nearly 100 psi[c] (0.7 MPa). When this type of cluster of peaks is observed, there seems to be little consistency in the number of peaks in the cluster, their relative amplitudes, or the spacing between peaks.

The curve in Figure 7B is typical of heavier loads of the Pyropak powder, all loads of the Newco powder, all but the heaviest loads of the MP Associates powder, and the lighter loads of the Astro powder. There is always a single peak, but it is not always symmetric. The peak shown in Figure 7B spans only about 2 ms in time and has a maximum pressure approaching 3000 psi (20 MPa).

The curve in Figure 7C is somewhat typical of the heavier loads of the MP Associates and Astro powders, and the lightest loads of the Theatre Effects and Precision Theatrical powders. These pressure pulses have one or more narrow high pressure peaks superimposed on a wider, lower more modest pressure peak. On some occasions the pressure pulses have fully developed oscillatory features as seen in the curve in Figure 7C, which only spans about 0.5 ms in time, with a maximum pressure exceeding 10,000 psi (70 MPa).

The curve in Figure 7D is typical for the higher loads (but still only about 10 grams) of the Theatre Effects and Precision Theatrical powders. The prominent portion of the pressure peak spans less than 0.1 ms, and the maximum pressure has risen to well over 50,000 psi (350 MPa).

It may be interesting to note for the powder types and load masses tested, even though the peak mortar pressures increased by a factor of approximately 500, the pressure impulse only increased by a factor of 3. Thus the primary difference is time span, over which the pressure pulse is produced, which decreases by a factor of approximately 200.

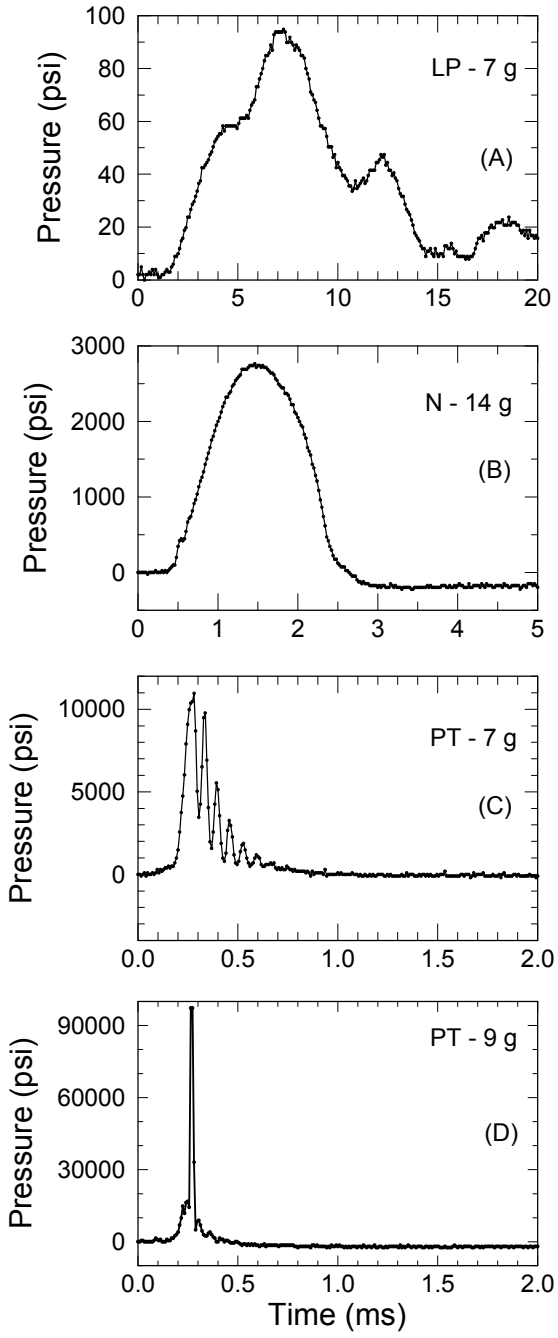

Figure 7. Examples of a variety peak shapes seen in internal mortar pressure data (note the differences in the time scales.)

Although the internal mortar pressure curves generally trend as discussed above, there are still major variations that occur for apparently identical loads of the same powder. For example, see Table 5 for 21 gram loads of the Astro powder. Here the maximum pressures were 34, 12, and 47 kpsi (230, 80, and 320 MPa, respectively). However, the pressure impulses were 4.4, 4.4, and 4.3 psi·s (30, 30, and 29 kPa·s), respectively, and the peak air blast overpressures were all 2.1 psi (14 kPa). In this case the total energy being released and the sound pressure levels are quite consistent. Independent of concussion powder type, this is generally true; air blast pressures correlate better with pressure impulse than with peak internal mortar pressure.

If it can be assumed that the tonal quality (sharper crack versus mellower boom) is a function of the durations of the positive and negative phases of the blast wave, then there may be noticeable differences in the tonal quality of sounds produced by the various powders. (Testing with human subjects is planned to investigate this.) Table 9 lists the average positive phase durations for the various powder types, each with load masses that produced approximately equal peak air blast overpressures (loudness). Figure 8 shows the air blast waves for the two extremes of the various cases. It may be of interest to note that the order of powder types in Table 9, by decreasing duration of positive phase, is the same as that in Table 8, where they were listed in order of increasing internal pressures for the same load mass.

A review of the data in Table 8 reveals that the durations of positive phase of the air blasts for the various powders is generally also a function of load mass. However, the functional relationship is different for the various powders. Note that for the three lowest pressure producing powders (LunaTech/Pyropak, Newco and MP Associates) the durations of positive phase decreases for increasing load mass. Note further that the opposite trend holds for the two highest pressure producing powders (Theatre Effects and Precision Theatrical). Finally, for Astro's powder, note that the duration of positive phase is essentially independent of powder load mass. These relationships are illustrated in

Table 9. Average Positive Phase Durations for Powder Loads Producing Air Blast Pressures of Approximately 1.5 psi (10 kPa).

Powder and Load (g) [a]	Blast (psi)	Pos. Phase (ms)
LP 28	1.3	2.0
N 21	1.6	1.4
MP 14	1.5	1.1
A 14	1.7	0.84
TE 9	1.6	0.78
PT 5	1.4	0.64

(For conversion of units: 1 psi = 6.89 kPa)

[a] LP = Luna Tech/Pyropak; N = Newco Products; MP = MP Associates; A = Astro Pyrotechnics; TE = Theatre Effects; and PT = Precision Theatrical.

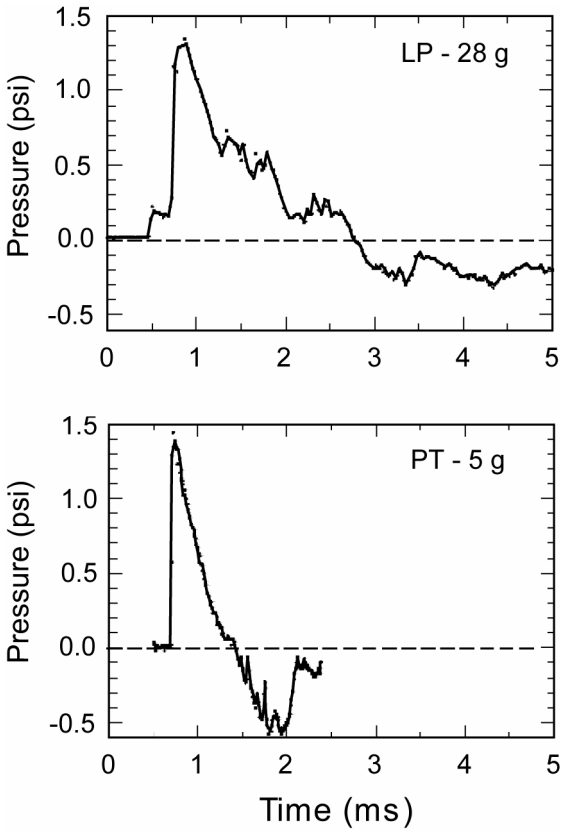

Figure 8. Air blast pressure curves illustrating the approximate range of differences in positive phase durations.

Figure 9, which is a graph of positive phase duration versus load mass (each normalized to the values for the smallest load mass) for the different powder types.

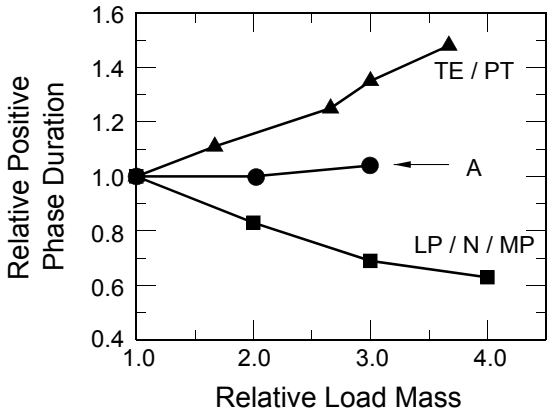

Figure 9. Graph of positive phase duration versus load mass (each normalized to the values for the smallest load mass) for the different powder types.

Conclusion

It was not the intention of this study to rate the performance of the concussion powders tested. In addition, further studies are needed before truly meaningful conclusions can be drawn. Planned studies include: the effect of distance on peak sound pressure levels and the duration of positive phase, and the loudness and tonal quality of the impulse sounds as perceived by human subjects. Accordingly, essentially no conclusions are presented in this paper.

Obviously the various powders tested have significantly different performance characteristics, thus offering the user a wider range of performance choices than might have been expected. It is hoped that the information in this article proves to be useful to consumers in selecting concussion powders that: (1) fit their needs, and (2) are compatible with the burst strength of their concussion mortars. Also, hopefully the participating manufacturers and other researchers find these results of general interest.

Acknowledgments

The authors gratefully acknowledge D. Hyman of Astro Pyrotechnics, T. DeWille of Luna Tech, D. Pier of MP Associates, A. Rozzi of Newco Products, R. Nickel of Precision Theatrical, and N. Kahn of Theatre Effects, for participating in this study by supplying samples of their concussion powders. In addition, the authors acknowledge that the electric matches used in this study were provided by D. Pier, and the concussion mortar was supplied by T. DeWille.

The authors are also grateful for the technical and editorial suggestions provided by M. Grubelich, L. Weinman, M. Williams, and John Bergman. The authors are also grateful for the assistance of R. Greenberg.

Notes

[a] Commercial sound pressure level (SPL) measuring instruments operated in "peak" mode, typically have a time constant of 50 μs. While this is fast for most sounds, it is still fairly slow for an air blast (shock) wave, which has an essentially instantaneous pressure rise, followed by a much slower (but still fast) decay to ambient pressure. Therefore, such an instrument will underestimate actual SPL's of the sounds of explosions. This is the same type instrument, with the same time constant, that is used to establish acceptable SPL's for human exposure. On the other hand, the instrument used in this study to measure air blast overpressure, from which sound pressure levels were calculated, has a rise time of only 4 μs. As a result, the instrument used in this study generates higher SPL's for the sounds of explosions than typical instruments would. This can be important, if the results of this study are compared with results using instruments with slower response or are compared with SPL regulations for acceptable human exposure. For the durations of positive phase seen in this study, the SPL's reported will range from about 1 to 2 dB higher than would have been measured using typical SPL instruments.

[b] It is fairly common in the authors' laboratory to work using a mixture of SI and English units. In this paper, for accuracy of reporting in the text, the actual units of measurement are given first, followed by their SI or English equivalent, with the same number of significant figures. In tables, generally only the actual units of measurement are reported, and conversion factors are appended to the tables. The authors apologize for any inconvenience this causes.

[c] Note that none of the pressure data presented in Figure 7 have been corrected for the presence of the silicone sealant. This only affects pressures less than about 2000 psi. For example, if corrected, the peak pressure in Figure 7A would actually be nearly 200 psi and not 100 psi as shown.

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2) S.W. Wilson, "Important Industry Warning—Potential Failure of Concussion Mortars", *Fireworks Business*, No. 151, 1996, p 2.

3) K.L. and B.J. Kosanke, "Brief Summary of Concussion Powder Test Results", *Fireworks Business*, No. 153, 1996, p 2.

4) *Encyclopedia of Physics*, Second ed., VCH Publishers, 1991, p 22.

5) *Van Nostrand's Scientific Encyclopedia*, Fifth ed., Van Nostrand Reinhold, 1976, p 25.

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7) Data collected by K.L. and B.J. Kosanke and M. Carter at the 1997 Western Winter Blast (annual convention) of the Western Pyrotechnic Association to be reported in a future article.

This article, which originally appeared in *High Power Rocketry*, May 1995, p 20, has been updated.

The Nitrous Oxide Hybrid Rocket Motor

"I might construct a rocket, in the form
Of a huge locust, driven by impulses
Of villainous saltpeter from the rear,
Upwards by leaps and bounds"

Cyrano in Cyrano de Bergerac, Act III

Al Jackson [TRA #1625]
4321 Jim West, Bellaire, TX 77401, USA

Technical Illustrations by Mark Rowley, TRA #1928

Introduction

High power model rocketry has its charms, besides the sound of the outward bound. Flying a vehicle to altitude, keeping it together near Mach and finding it (after it has totally gone out of sight!)... in high power rocketry that can be quite a challenge! Recent years have seen the introduction of electronic devices both for aerobraking deployment and sequencing. We have seen high tech building materials, such as carbon composites, in high power rocketry (HPR) models. We have also seen a growth in sophistication in the standard solid rocket motors, especially with the introduction of reloads. Growth of the hobby has also drawn the attention of more regulatory agencies to solid rocket motors. Time has come for the introduction in HPR of a new propulsion technology.

Modern solid rocket motors employ propellants that insulate the walls from hot combustion products. The propellants usually are a mixture of oxidizer crystals, such as ammonium perchlorate held in a matrix of synthetic rubber (or plastic) binder along with an additive like aluminum powder. A solid motor allows for possible thrust vector control but it is difficult to throttle. Solids are relatively cheap and simple and have been very attractive for military purposes. Liquids are still the motor of choice for heavy duty orbital supply and have a long history. Though we may see liquid rocket motors move from the realm of commercial, military and amateur rocketry to HPR, it is probably a long way off. For high power model rockets there is an attractive alternative: the hybrid rocket motor.

Hybrid Rocket Motor Operation

The hybrid rocket motor usually employs propellants in two different states of physical composition. The prevalent concept is a solid fuel, such as a polymer, and a liquid or gaseous oxidizer such as oxygen (O_2), hydrogen peroxide (H_2O_2) or nitrous oxide (N_2O). Figure 1 is a schematic diagram of a hybrid motor. A pressure or pump system feeds a liquid or gaseous oxidizer into the combustion chamber, which contains the fuel as a solid component. The solid grain in Figure 1 has a single hollow circular cylinder as a flame channel called the grain port. Once ignition is initiated combustion products then converge toward the nozzle throat where they attain the speed of sound and expand in the diverging section of the nozzle reaching supersonic speeds. (One can turn the system around and have a liquid fuel and solid oxidizer, but in general this system has some disadvantages.)[1]

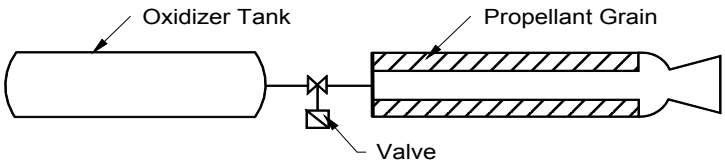

Figure 1. A schematic diagram of a hybrid motor.

A more detailed elaboration of the combustion process and flame structure is shown in Figure 2. Combustion in a hybrid rocket motor differs substantially from that in a solid or liquid fuel rocket. The oxidizer, after having been turned into a mixture of droplets and gasified liquid by the injector, streams through the combustion channel during the operation of the motor. A boundary layer is formed above the surface of the grain. This layer is fed by the oxidizer entering from the port side of the grain and by gasified fuel ablating from the grain wall.

What makes hybrid rocket motors so attractive is that they combine the advantages of both solids and liquids. There is improved safety in handling, since there is no intimate mixing of fuel and oxidizer as with solids, and the separate components can, in general, be handled with ease. Because thrust is proportional to oxidizer flow rate and internal surface area, one can consider the possibility of throttling. Another advantage is that the hybrid solid fuel component can have superior mechanical properties over the grains in a solid rocket motor.

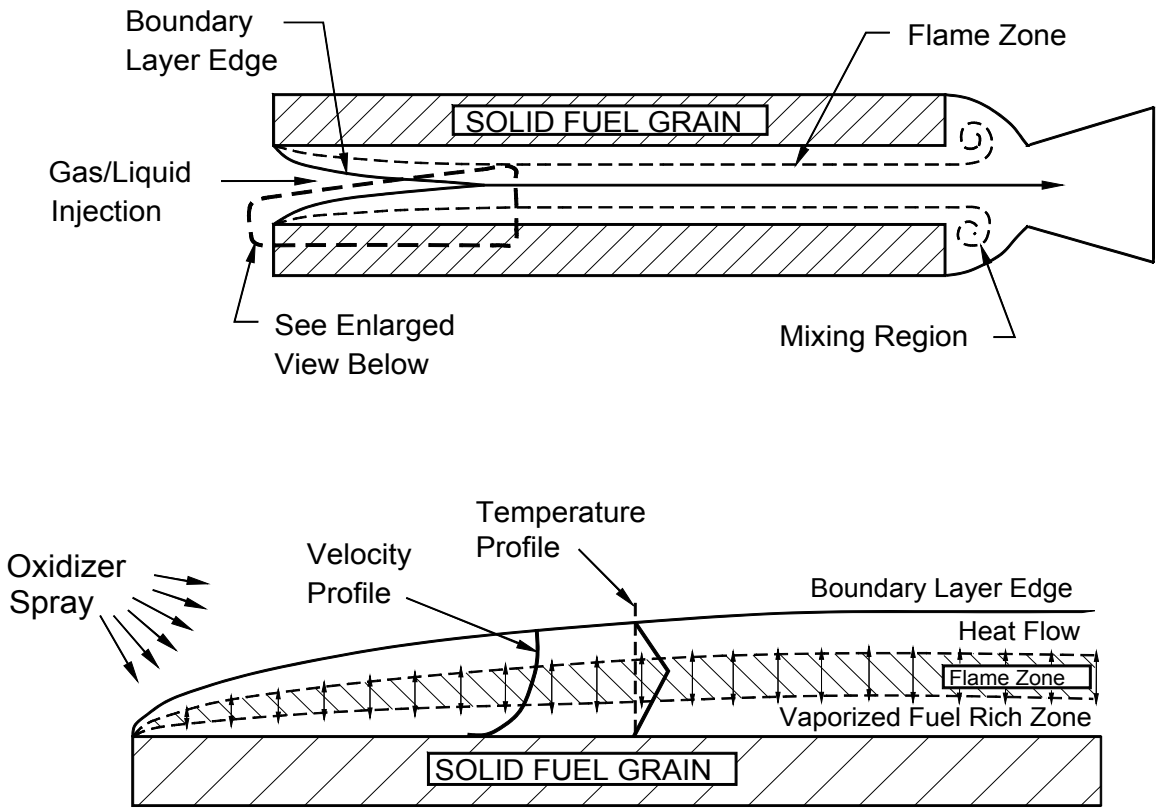

Figure 2. A more detailed diagram of the combustion process and flame structure.

To this one may add that advantages in handling and storage for hybrids bypass many of the regulatory problems at the moment with large solid motors used in high power rocketry.

Hybrids also have some disadvantages: There can be a varying specific impulse during operation and steady state combustion efficiencies that can be lower than liquids and solids. However, these are factors of more interest in very large rocket systems. The hybrid rocket motor is simpler than a liquid bipropellant rocket motor, but not as simple as a conventional solid propellant motor. Hybrids are also subject to the same combustion stability problems as solids and liquids but this probably will not affect operations as far as the high power enthusiast is concerned.

Some History of Hybrid Rocket Motors[2,3]

1929: The German film company UFA wanted a publicity stunt for their production of Fritz Lange's science fiction film *Woman In The Moon*; so they hired H. Oberth to launch a demonstration rocket. Oberth designed several rockets, but the one he finally settled on was a vehicle using a hybrid rocket motor. It was to operate on liquid oxygen as the oxidizer and carbon rods as the fuel. The combustion products were to be expelled from the top of the rocket for thrust. Some hardware was built and some tests made but the motor was never constructed or flown.

1933: The first hybrid rocket motor to actually fly was developed in the Soviet Union by S. P. Korolev and M. K. Trikhonravov as part of the GIRD program. The propellants were liquid oxygen and a colloidal suspension of benzine. A vehicle with this motor flew to 1500 meters in 1934.

1937: The German company I.G. Farben supported research by a group of their engineers, L. Andrussow, O. Lutz and W. Noeggerath who developed several hybrid rocket motors. They tested a nitrous oxide (N_2O) and coal fueled motor with a thrust of 10,000 newtons. This motor was tested with burn times of up to 120 seconds. One finds no reference to this motor ever powering a vehicle, but it is the first instance (and last! for a long time) of a nitrous oxide hybrid rocket motor.

Late 1930's to Early 1950's: The California Rocket Society and Pacific Rocket Society (PRS) built and tested a number of hybrid rocket motors. The PRS conducted a number of tests in the late 1940's using liquid oxygen as the oxidizer. Some of the fuel grains used were Douglas Fir(!), wax loaded with carbon black and synthetic rubber. A LOX-rubber [LOX = liquid oxygen] motor flew in June of 1951 reaching an altitude of 30,000 feet.

Late 1940's to present: US industrial interest in hybrids started in the late 1940's with work by engineers such as G. Moore and K. Berman at General Electric. They published an important paper about their H_2O_2 motor in the American Rocket Society's journal *Jet Propulsion* in 1956[4]. Since the mid fifties there has been a small but steady program to develop hybrids. It's not entirely clear why liquid and solid rocket motors were developed to an order of magnitude more in proportion than hybrids throughout the 1960's and 1970's.

The only hybrid rocket motor to go into production was the power plant for the Air Force target drones Sandpiper and HAST vehicles in the late 1960's. These were large throttleable hybrid rocket motors. There was also hybrid military developments in the former Soviet Union, but these are not well documented.

American Rocket Company (AMROC), founded in the mid 1980's, has now become the chief proponent and developer of hybrid rocket motors. A large 10,000 pound thrust N_2O motor was tested around 1989.[5] AMROC even demonstrated a hybrid motor that used an Italian salami as a fuel grain and liquid oxygen as the oxidizer. After the firing, the spectators ate the 'cooked fuel grain' and commented it had a delicious BBQ flavor. This, of course, conjures in the rocketeer the idea of having a launch and lunch all in one flight.

In the early eighties members of the Reaction Research Society (RRS) started to investigate the possibility of small hybrid rocket motors. In the early 1980's RRS members Bill Wood and Korey Kline speculated on the use of N_2O as an oxidizer in a small hybrid. By the early 1990's several small hybrids had been tested by the RRS, including early N_2O hybrids by Kline and an H_2O_2 hybrid built by Mark

Ventura. Independently, M. Grubelich, J. Rowlands and L. Reese[6] have also tested some small N_2O motors. Early in 1994 the company Hypertek began experiments with small hybrid motors. Later in 1994 Hypertek and AeroTech announced future availability of hybrid motors for rocketeers.

Choice of an Oxidizer

The attractiveness of hybrid motors immediately suggests itself to any high power model rocketeer who has used solid rocket motors. The fuel grain is made almost the same way except for the absence of an oxidizer. The main difference is an oxidizer that exists in a liquid or gaseous state. Since rocket motor oxidizers can have hazardous properties that range from critical injury to sudden death, one is limited when looking for a safe oxidizer for use in a hobby. Looking through a list of oxidizers, three suggest themselves: liquid or gaseous oxygen (O_2), hydrogen peroxide (H_2O_2) and nitrous oxide (N_2O). Liquid oxygen, ubiquitous in big rockets, presents cryogenic problems while gaseous oxygen has a tankage weight penalty. Hydrogen peroxide in concentrations less than 80% is a possibility, but would necessitate a separate pressurizing system and has availability problems at this concentration.

Nitrous oxide is quite interesting as an oxidizer (see Figure 3). It is in a liquid state under pressure at 70 °F. Its vapor pressure at 70 °F is about 750 pounds per square inch and has a density of approximately 47 pounds per cubic foot at this temperature and pressure. For some reasonable motor chamber pressures there is no need for a separate pressurization system because of these properties. In fact, N_2O is an example of a self-pressurizing blowdown system.

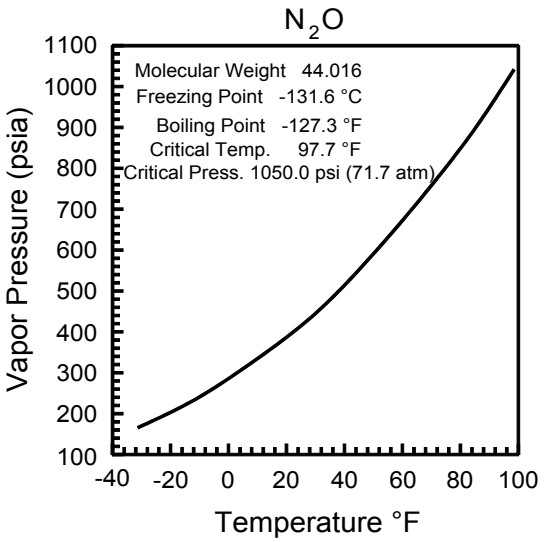

Figure 3. Nitrous oxide equation of state.

A survey of older literature turns up very little mention of N_2O as an oxidizer. The use of N_2O in a hybrid motor in Germany, as mentioned above, seems to be one of the few before some use in the Soviet Lunar program. This is because, relatively speaking, N_2O has a modest performance compared to other oxidizers. However, a graph of comparisons in Sutton[7] is quite interesting. One sees a theoretical specific impulse of over 200 for N_2O and HTPB. (See also Estey and Whittinghill.[8]) NOTE! Nitrous oxide (N_2O) is *not* the same as nitric oxide (NO_2) which is nasty stuff.

Nitrous oxide presents no significant health hazard.[9] It is nontoxic and nonirritating and has been used as an anesthetic in medicine and dentistry (it still carries the generic name of 'laughing gas'). It even forms a minor constituent of the natural atmosphere.[10] One notes, though it has been used as a mild intoxicant, it is also a simple asphyxiant. However, it is available in a 'denatured' form with approximately 200 ppm of sulfur dioxide (SO_2) added. Pure nitrous oxide is classified with a DOT label as Nonflammable gas. It will, however, support combustion. Above 572 °F, it dissociates and becomes a strong oxidizing agent. Since it is stored under pressure, one should take handling precautions as with any high pressure gas. Prudent handling of possible igni-

tion sources in the vicinity of N_2O storage bottles is warranted.

WARNING! *Any N_2O oxidizer vessel should not be overfilled! Expansion of N_2O as a liquid may overwhelm any pressure relief system causing a system failure and an explosion.*

Denatured N_2O is available to the general public, though one should check local and state regulations. It has been a standard component of performance cars for a long time and many speed equipment hobbyists have used it for years. Your local speed shop may carry denatured N_2O. A check of local sources finds it priced in a range of $1.25 to $2 per pound.

Performance

How well does nitrous oxide perform as an oxidizer? Impulse or momentum change is more important in rating rockets motors than energy dissipated and hence a common figure of merit is the quantity specific impulse, I_{sp}, which is a function of thrust, F (in lbs) and unit weight flow rate, dw/dt (in lbs/s)

$$I_{sp} = F/(dw/dt) = F \bullet t/m_p g \quad \text{(in s)}$$

where t is the motor operating time, m_p is mass of propellant, and g is the acceleration of gravity. Specific impulse can be expressed in terms of thrust chamber conditions and propellant thermochemistry:

$$I_{sp} = \sqrt{\frac{2k}{k-1}\,\frac{RT_c}{g\overline{M}}\left[1-\left(\frac{p_e}{p_c}\right)^{\frac{k-1}{k}}\right]}$$

where:

R = universal gas constant, 1544 ft-lb/mol degrees Rankine;
g = acceleration of gravity, 32.2 ft/s^2;
T_c = chamber temperature, degrees Rankine;
p_e = chamber exhaust pressure, psi;
p_c = chamber pressure, psi;
$\overline{M}$ = mean molecular weight, lb/mol;
k = ratio of specific heats.

Figure 4 shows the output from a computer program which computes specific impulse as a function of oxidizer to fuel ratio (o/f) for a given chamber pressure, nozzle exit pressure and thermochemical characteristics of a fuel, in this case hydroxyl/terminated polybutadiene (HTPB), and an oxidizer N_2O. One sees that the optimum oxidizer to fuel ratio is near eight and that performance is better for higher chamber pressures. For those concerned about such things let us note here the exhaust products from the theoretical calculation. One thus sees that the N_2O hybrid has a performance quite suitable for high power model rockets. (For the technically minded, a sketch of an example motor design is given in the Appendix.)

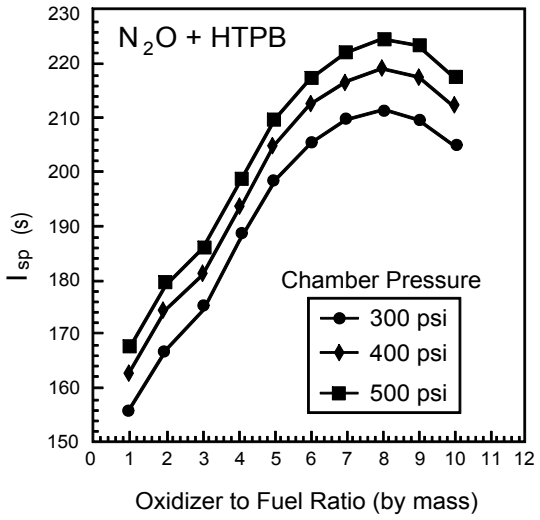

Figure 4. The output from a computer program that computes specific impulse as a function of oxidizer to fuel ratio (o/f).

The chemical exhaust products from a theoretical computation for a HTPB and N_2O combination are: 60% N_2, 19% H_2O, 19% CO_2, 1% CO and 1% other chemical exhaust products. All are normal atmospheric components. This makes hybrids even safer as emitters of polluting effluents than solid rocket motors.

Flying a Hybrid

Flying a hybrid will be almost like flying a large high power solid rocket motor. Motor

prep will be similar to that of the standard reloads used now. A plastic or rubber propellant grain will be placed in the chamber and secured. There may be reusable or disposable nozzles. The whole system may use a process of loading the N_2O on the launch pad or the N_2O vessel filled separately and assembled with the motor. (We note that as with any high pressure fluid delivery system an allowance will have to be made for 'ullage', that is some volume for gas expansion is allocated. Currently, about 30% ullage is maintained by those engaged in high performance car activities.) Some provision for weighing the N_2O must also be made. Igniters may be both nonpyrotechnic and pyrotechnic, but the whole system will launch pretty much in a manner similar to that of current high power model rockets.

There are currently two manufacturers preparing to make offerings of N_2O hybrid rocket motors: Hypertek and AeroTech. We put some questions to them about their systems and here are their answers:

HPR: In what power ranges are there likely to be hybrid motors available… K and up? Smaller? Only larger?

Hypertek: Initially J to K motors, but we've designed as low as G and as high as O. It depends largely on interest expressed to us.

AeroTech: AeroTech's first RMS/Hybrid offering will be in the 54 mm H, I and J classes.

HPR: How do you mount the N_2O tank? Will most of our HPR model rockets be usable? Or more, how is the overall motor mounted?

Hypertek: The tank is mounted above the motor. The injector manifold, combustion chamber and nozzle are one-piece construction, injection molded. The motor consists, then, of two pieces; the lower (combustion chamber) portion of which is single use. Whether existing airframes can be used depends on the free space available above the motor section.

AeroTech: The RMS/Hybrid N_2O cylinder is mounted directly to the RMS casing via a special forward closure fitting. Approximately 30" of 54 mm motor mount tube will be required to accommodate the longest 54 mm casing/cylinder combination.

HPR: Are hybrid thrust profiles different from current composite motors?

Hypertek: Our motor is slightly regressive. We can vary the thrust profile to suit different missions. There will be a means of adjusting the flow rate of N_2O into the motor such that thrust can be adjusted from 35 lbs to 110 lbs on the low end, and from 60 lbs to 200 lbs on the high end.

AeroTech: AeroTech's curves will exhibit regressive time/thrust profiles.

HPR: What is the expected cost-per-flight? Give a couple of examples, for K, L, or whatever. How about the initial motor cost?

Hypertek: Expected cost per flight will be $20.

AeroTech: Expected cost per flight will be in the 1/2–1/3 range of current solid propellant RMS prices. Street price for the RMS/Hybrid "J" reload should be in the $25–30 range.

HPR: How are the tanks reloaded? Do we do that? What do hot conditions do to a N_2O tank sitting on the pad?

Hypertek: Users fill the tank immediately prior to launch. Hot weather raises the tank pressure, but not beyond design parameters. The oxidizer tank will only be filled on the pad and not transported under pressure. A pad launcher-fill system will be a part of the system. (A dump valve is part of the system to purge the tank on the pad if needed.)

AeroTech: The RMS/Hybrid N_2O cylinders can be refilled at an auto speed shop, commercial gas supplier or by the user with a 10–15 pound N_2O cylinder (also commercially available), a transfer hose and a special adaptor fitting. A gram scale will be necessary to obtain an accurate fill weight in accordance with DOT regulations. AeroTech will develop refilling procedures and instructions for use by RMS/Hybrid customers.

HPR: Given the design of the motor, do hybrid systems assume/require an independent ejection system (altimeter, timer, etc.)?

Hypertek: The recommended system is either altimeter or R/C [R/C=Radio Controlled], but other systems are being considered for release.

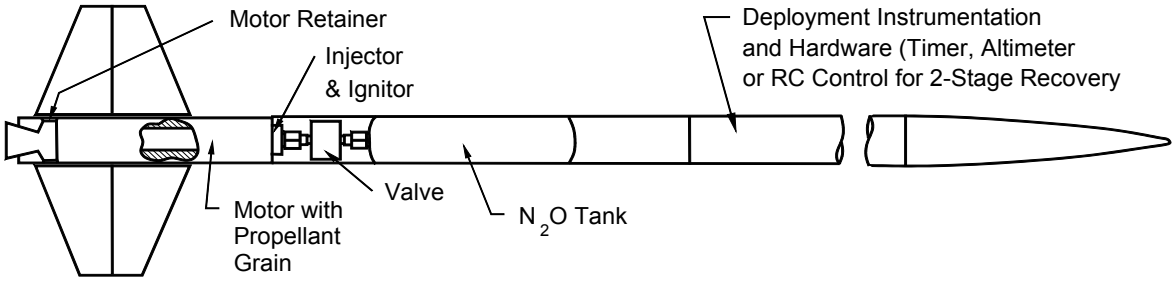

Figure 5. Sketch of a possible model hybrid motor combination.

AeroTech: The design of the RMS/Hybrid motor will require an independent recovery activation system.

HPR: What are the safety concerns of hybrid motors? How do these differ from HPR composite motors?

Hypertek: Hybrids are much safer than solids and don't share the common failure modes of solids. Our hybrid system is inert when not running.

AeroTech: The safety concerns of hybrid motors revolve primarily around the handling of compressed gases. Cylinder specifications, filling procedures, cylinder attachment, valves, contaminates and personal protective equipment are some of the issues that will need to be addressed in hybrid–oriented safety codes and motor certification standards. Of course, many of the existing safety issues regarding solid propellant HPR motors also apply, such as safe casing failure modes, repeatable performance, etc.

HPR: What is the ignition system?

Hypertek: The ignition system consists of a combination of a small electrical heating system combined with gaseous oxygen. It is a nonpyrotechnic system. A hold-down link is burned through during ignition. This integral part of the system is needed to hold the pressured tank on the pad.

AeroTech: The ignition system of the RMS/Hybrid is currently proprietary, but virtually all HPR igniters should be capable of initiating the RMS/Hybrid motor in less than one second.

Figure 5 shows a possible model-hybrid motor combination. The motor may be 'taped' in as has been done in high power rocketry, but it's recommended that a more substantial retention system be used. Remember, one will have to supply an independent deployment system as indicated.

Conclusions

It would seem exciting times are ahead for high power model rocketeers! The N_2O hybrid offers another fun aspect for flyers who like the challenge of sophisticated model rocket systems. Those flyers, interested in altitude, will have an expanded opportunity to gain those desired long-burn thrust profiles. I can even see the ambitious building on-board computers that allow for thrust programming and attainment of real trajectory optimization.

The hybrid offers a safe and reliable rocket motor for those interested in high impulse. Shipping costs of hardware and fuel grains will be small; no HAZMAT [HAZMAT=Hazardous Material] charges for inert materials! Much, much fewer regulatory problems if any at all! But better yet is the price-per-flight! J, K, L and maybe even higher total impulse motor cost per flight will be even less than what reload grains cost now! The up-front system cost will probably be in the range of the more costly reload system, but at 20 bucks and less per flight, amortization will be fast.

Acknowledgments: We wish to thank Dr. Robert Schmucker, Mark Grubelich, Hypertek and AeroTech for comments and suggestions.

Appendix A

Sketch of a Motor Design[1,2,7,8,11]

Once a propellant combination is known, and its specific impulse computed for a given chamber pressure, one may start rocket chamber layout. One is mindful of a caveat, even knowing the theoretical performance: systems efficiency and overall system interfacing will affect rocket motor efficacy. Actually motor development is more than just computing the dimensions of a motor; it takes much experimental and empirical work to make an efficient motor.

For a hybrid grain, design is of fundamental importance. In the simplest configuration, an injector sprays the oxidizer down a hollow cylinder of fuel (see Figure 2). The channel in which combustion takes place is called a 'port' just as it is in the case of a solid rocket motor. Combustion takes place in a narrow zone which is fed by gaseous decomposition of solid fuel and gases from the liquid oxidizer. The most important factor which determines fuel consumption is the velocity (*dr/dt*), which the fuel regresses in a direction at right angles to the original surface of the grain port. The laws governing the regression rate in a hybrid engine, just as in the case of a solid fuel rocket, constitute a decisive problem. The regression rate depends on various parameters, but the dominant one is the mass rate of gases (G) in the combustion channel usually defined as:

$$G = dm/dt \,/\, A_p \qquad (\text{lb/in}^2\text{-s})$$

where A_p is the port cross section area. For our purposes, the most useful functional form for dr/dt is given by the relation

$$dr/dt = a \cdot G_o^{\,n} \qquad (\text{in/s})$$

where G_o is the oxidizer mass rate, and a and n are constants. Small hybrid motors have regression rates that range from 0.1 to 0.01 in/s. From reference 11 we will take the average value of a = 0.1 and n = 0.8 for calculation purposes.

Let us look at an example motor design. Suppose you want to make a 50-lb thrust motor for a time duration of five seconds with a motor efficiency (e_f) of 90%. This makes an approximate 1100 newton second motor, or an approximate J220. Take the chamber pressure as 500 lbs/in^2 and the fuel and oxidizer to be HTPB and N_2O at a mixture ratio of o/f = 8. A theoretical thermochemical calculation shows an I_{sp} of 224.3 s, thrust coefficient (C_f) of 1.50, expansion ratio e of 5.2, and a chamber temperature of 5010 °F. The dimensions of the nozzle, injector and fuel grain are then computed from these specifications.

The nozzle configuration follows from thermodynamic theory. Using the thrust, thrust coefficient, the efficiency and chamber pressure p_c one has for the throat area

$$A_t = F \,/\, (e_f\, C_f\, p_c) \qquad (\text{in}^2)$$

and exit area is

$$A_e = e \bullet A_t \qquad (\text{in}^2)$$

From these, the throat and exit diameters can be calculated. The total weight flow rate *dw/dt* can be written as

$$dw/dt = p_c\, A_t\, C_f/(e_f\, I_{sp}) \qquad (\text{lb/s})$$

which splits into the oxidizer dw_o/dt and fuel flow dw_f/dt rates

$$dw_o/dt = (o/f)(dw/dt)/[(o/f)+1] \qquad (\text{lb/s})$$

$$dw_f/dt = (dw/dt)/[(o/f)+1] \qquad (\text{lb/s})$$

From the given operating time, the initial oxidizer and fuel weights can be calculated.

The injector is taken as a single orifice with a discharge coefficient of C_d, then if the oxidizer density is given by ρ, with the pressure drop taken as Δp (psi), then the injection velocity is given by

$$v = C_d\sqrt{(2g\Delta p/\rho)} \qquad (\text{ft/s})$$

and the area of the injector hole (or holes) is given by

$$A_o = \rho\,(dw_o/dt)/v \qquad (\text{in}^2)$$

The grain design can be computed from the following. The motor chamber diameter is taken as d_{cm} and the grain is taken with a single cylindrical port. Let the final radius of the grain port be r_f. This should be taken so a margin of protection for the outer chamber walls is given. For a given time (t) and radius of the final port, the initial port (r_p) is given by

$$r_p^{2n+1} = r_f^{2n+1} - a(2n+1)\, t(dw_o/dt/\pi)^n \qquad \text{(in)}$$

and the grain length is computed from

$$l_g = (dw_f/dt)/(2\pi r_p \rho r_r) \qquad \text{(in)}$$

where ρ is the fuel density and r_r = regression rate = dr/dt.

For the given motor parameters, the results of a calculation are shown in Table 1. Several things are of note. Because the oxidizer to fuel ratio is quite high, only a small amount of fuel is needed. Thus, one can probably make the fuel grains with quite a margin for wall protection. One can envisage that the grains would be like the standard reload grains for the solid rocket motors used now. The total oxidizer rate of nearly 0.3 pounds per second may be quite high for small solenoid valves available from, say, speed shops. In the design of a rocket motor, valving is a crucial matter to keep in mind. The valve and plumbing from the N_2O tank should be designed so that the flow is smooth and as laminar as possible. An undersized line or a valve with mismatched flow coefficient can lead to turbulence.

That constitutes an outline of motor design. Making a flight-weight hybrid motor is yet another challenge. Valves must be selected or designed with care and not weigh too much. The pressure vessels envisioned right now mostly seem to be of aluminum which can be heavy. It may be possible to use filament wound casings of composite materials. One must be mindful of system mass ratios for the kinds of motors; so it will be interesting to see if someone can build a hybrid in the E, F and G range.

Table 1. Example Motor Design.

Thrust Coefficient	1.50
Motor Efficiency	0.90
Thrust	50.00 lb
Duration	5.00 s
Chamber Pressure	500.00 psia
Chamber Temperature	5010 °F
Specific Impulse	224.3 s
Exhaust Velocity	4811 feet/s
Area Ratio	5.22
Chamber Diameter	2.50 in.
Throat Diameter	0.31 in.
Exit Diameter	0.70 in.
Nozzle Length	2.64 in.
Oxidizer Flow Rate	0.22 lb/s
Fuel Flow Rate	0.03 lb/s
Total Flow Rate	0.25 lb/s
Total Flow	1.24 lb
Total Oxidizer	1.10 lb
Total Fuel	0.14 lb
Pressure Drop Across Injector	100.00 lb/in.^{2}
Diameter of Injector	0.093 in.
Injector Speed	112.93 ft/s
Grain Length	10.71 in.
Regression Rate Exponent	0.80
Regression Rate Coefficient	0.10
Initial Port Radius	0.94 in.
Regression Rate	0.01 in./s

References

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11) P. Estey, D. Altman, and J. McFarlane, *An Evaluation of Scaling Effects for Hybrid Rocket Motors,* AIAA paper AIAA–91–2517, 1991.

Update: Both Aerotech and Hypertek introduced their hybrid motors for high power model rocketry in the spring of 1995, and both have enjoyed wide use by hobbyists for the last year and a half.

Appendix B

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HYBRID-3.BAS [listed below] is a BASIC adaptation of Al Jackson's FORTRAN program used in developing numbers for the design example listed in the appendix of his article, "The Nitrous Oxide Hybrid Rocket Motor". It can be run using GWBASIC (available on PC systems using MS-DOS through version 5) or QBASIC (on PC systems using MS-DOS version 6) or it can be run with or compiled and run with QUICKBASIC. It requires the data file MOTOR.DAT to produce output. If one wishes to run other examples, the data file or program could be easily modified to accept keyboard input of data. If one does not have access to a computer or any of the versions of BASIC mentioned, the listing can be used as a guide for manual computations. As is usually the case, it is very important to use consistent units when doing calculations. The program can also be used as a skeleton to build a much more elaborate design program. In most cases, nonprogrammers can read BASIC programs and follow the calculations done in them.

```
10 '  Al Jackson;s Fortran Program "Hybrid" converted to Basic
20 '  APRIL 9, 1997
30 '  Some changes made from original program
40 '  e.g., Conversion to Fahrenheit corrections etc.
50 '  Uses input file "motor.dat"
60    CLEAR : CLS : OPTION BASE 1: GRAVITATIONAL.CONSTANT = 32.174: PI = 3.14159
70 '          INITIALIZE INPUT VARIABLES
80   THRUST.COEFFICIENT = 0
90   SPECIFIC.IMPULSE = 0
100 THRUST = 0
110 EXPANSION.RATIO = 0
120 CHAMBER.TEMPERATURE = 0
130 CHAMBER.PRESSURE = 0
140 BURN.TIME = 0
150 MOTOR.EFFICIENCY = 0
160 OXYGEN.TO.FUEL.RATIO = 0
170 CHAMBER.DIAMETER = 0
180 INJECTOR.DISCHARGE.COEFFICIENT = 0
190 INJECTOR.DELTA.PRESSURE = 0
200 OXIDIZER.DENSITY = 0
210 FUEL.REGRESSION.COEFFICIENT = 0
220 FUEL.REGRESSION.EXPONENT = 0
230 FUEL.DENSITY = 0
240 FINAL.GRAIN.RADIUS = 0
```

```
250 '        INPUT SUBROUTINE
260 OPEN "MOTOR.DAT" FOR INPUT AS #1
270   LPRINT : LPRINT "INPUT DATA:"
280   INPUT #1, THRUST.COEFFICIENT: LPRINT "THRUST COEFFICIENT =";
      THRUST.COEFFICIENT
290   INPUT #1, SPECIFIC.IMPULSE: LPRINT "SPECIFIC IMPULSE ="; SPECIFIC.IMPULSE;
      "SECONDS"
300   INPUT #1, THRUST: LPRINT "THRUST ="; THRUST; "LBS"
310   INPUT #1, EXPANSION.RATIO: LPRINT "EXPANSION RATIO ="; EXPANSION.RATIO
320   INPUT #1, CHAMBER.TEMPERATURE: LPRINT "CHAMBER TEMPERATURE ="; CHAM-
      BER.TEMPERATURE; "DEGREES KELVIN"
330   INPUT #1, CHAMBER.PRESSURE: LPRINT "CHAMBER PRESSURE ="; CHAMBER.PRESSURE;
      "PSIA"
340   INPUT #1, BURN.TIME: LPRINT "BURN TIME ="; BURN.TIME; "SECONDS"
350   INPUT #1, MOTOR.EFFICIENCY: LPRINT "MOTOR EFFICIENCY ="; MOTOR.EFFICIENCY
360   INPUT #1, OXYGEN.TO.FUEL.RATIO: LPRINT "O/F RATIO ="; OXYGEN.TO.FUEL.RATIO
370   INPUT #1, CHAMBER.DIAMETER: LPRINT "MOTOR DIAMETER ="; CHAMBER.DIAMETER
380   INPUT #1, INJECTOR.DISCHARGE.COEFFICIENT: LPRINT "INJECTOR DISCHARGE COEFFI-
      CIENT ="; INJECTOR.DISCHARGE.COEFFICIENT
390   INPUT #1, INJECTOR.DELTA.PRESSURE: LPRINT "INJECTOR PRESSURE DROP ="; INJEC-
      TOR.DELTA.PRESSURE; "PSI"
400   INPUT #1, OXIDIZER.DENSITY: LPRINT "OXIDIZER DENSITY ="; OXIDIZER.DENSITY;
      "LB/CU FT"
410   INPUT #1, FUEL.REGRESSION.COEFFICIENT: LPRINT "REGRESSION RATE COEFFICIENT =";
      FUEL.REGRESSION.COEFFICIENT
420   INPUT #1, FUEL.REGRESSION.EXPONENT: LPRINT "REGRESSION RATE EXPONENT =";
      FUEL.REGRESSION.EXPONENT
430   INPUT #1, FUEL.DENSITY: LPRINT "FUEL DENSITY ="; FUEL.DENSITY; "LBS/CU FT"
440   INPUT #1, FINAL.GRAIN.RADIUS: LPRINT "FINAL CORE RADIUS ="; FI-
      NAL.GRAIN.RADIUS; "INCHES"
450   LPRINT : LPRINT : LPRINT "OUTPUT RESULTS:"
460 CLOSE #1
470 '        NOZZLE SUBROUTINE
480 NOZZLE.THROAT.AREA = THRUST / (CHAMBER.PRESSURE * MOTOR.EFFICIENCY *
      THRUST.COEFFICIENT)
490 NOZZLE.EXIT.AREA = NOZZLE.THROAT.AREA * EXPANSION.RATIO
500 NOZZLE.THROAT.DIAMETER = SQR(4 * NOZZLE.THROAT.AREA / PI)
510 NOZZLE.EXIT.DIAMETER = SQR(4 * NOZZLE.EXIT.AREA / PI)
520 NOZZLE.THROAT.RADIUS = NOZZLE.THROAT.DIAMETER / 2
530 NOZZLE.EXIT.RADIUS = NOZZLE.EXIT.DIAMETER / 2
540   NOZZLE.DIVERGENT.LENGTH = (NOZZLE.EXIT.RADIUS - NOZZLE.THROAT.RADIUS) /
      .267949   ' DIVIDED BY TANGENT 15 DEGREES
550   NOZZLE.CONVERGENT.LENGTH = ((CHAMBER.DIAMETER / 2) - NOZZLE.THROAT.RADIUS) /
      .57735       ' DIVIDED BY TANGENT 30 DEGREES
560   NOZZLE.THROAT.LENGTH = 0
570 NOZZLE.LENGTH = NOZZLE.CONVERGENT.LENGTH + NOZZLE.DIVERGENT.LENGTH + NOZ-
      ZLE.THROAT.LENGTH
580 '        PERFORMANCE SUBROUTINE
590 CHAR.EXHAUST.VELOCITY = SPECIFIC.IMPULSE * GRAVITATIONAL.CONSTANT /
      THRUST.COEFFICIENT
600   CSTAR = CHAR.EXHAUST.VELOCITY
610 TOTAL.PROPELLANT.FLOW.RATE = GRAVITATIONAL.CONSTANT * CHAMBER.PRESSURE * NOZ-
      ZLE.THROAT.AREA / CSTAR
620   OXIDIZER.FLOW.RATE = TOTAL.PROPELLANT.FLOW.RATE * OXYGEN.TO.FUEL.RATIO / (OXY-
      GEN.TO.FUEL.RATIO + 1)
630   FUEL.FLOW.RATE = TOTAL.PROPELLANT.FLOW.RATE / (OXYGEN.TO.FUEL.RATIO + 1)
640 '        PORT SUBROUTINE
650 SUB.ONE = FUEL.REGRESSION.COEFFICIENT * (2 * FUEL.REGRESSION.EXPONENT + 1)
660 SUB.TWO = (OXIDIZER.FLOW.RATE / PI) ^ FUEL.REGRESSION.EXPONENT
670 SUB.THREE = FINAL.GRAIN.RADIUS ^ (2 * FUEL.REGRESSION.EXPONENT + 1)
680 SUB.R = SUB.THREE - SUB.ONE * SUB.TWO * BURN.TIME
690 INITIAL.GRAIN.RADIUS = SUB.R ^ (1 / (2 * FUEL.REGRESSION.EXPONENT + 1))
700 '        GRAIN SUBROUTINE
710 PORT.CROSS.SECTIONAL.AREA = PI * (INITIAL.GRAIN.RADIUS) ^ 2
720 OXIDIZER.MASS.RATE = OXIDIZER.FLOW.RATE / PORT.CROSS.SECTIONAL.AREA
730 REGRESSION.RATE = FUEL.REGRESSION.COEFFICIENT * OXIDIZER.MASS.RATE ^
      FUEL.REGRESSION.EXPONENT
740 GRAIN.LENGTH = FUEL.FLOW.RATE / (2 * PI * INITIAL.GRAIN.RADIUS * FUEL.DENSITY *
      REGRESSION.RATE)
```

```
750 '         INJECTOR SUBROUTINE
760 GRAVITATIONAL.CONSTANT = GRAVITATIONAL.CONSTANT * 12        ' CONVERT TO
      INCHES/SECOND
770 OXIDIZER.DENSITY = OXIDIZER.DENSITY / 1728                  ' CONVERT TO LBS/CU
      IN
780 TEMP.ONE = TOTAL.PROPELLANT.FLOW.RATE
790 TEMP.TWO = INJECTOR.DISCHARGE.COEFFICIENT * SQR(2 * GRAVITATIONAL.CONSTANT *
      OXIDIZER.DENSITY * INJECTOR.DELTA.PRESSURE)
800 INJECTOR.AREA = TEMP.ONE / TEMP.TWO
810 INJECTOR.DIAMETER = SQR(4 * INJECTOR.AREA / PI)
820 INJECTOR.VELOCITY = INJECTOR.DISCHARGE.COEFFICIENT * ((2 * GRAVITA-
      TIONAL.CONSTANT * INJECTOR.DELTA.PRESSURE) / OXIDIZER.DENSITY) ^ .5
830 INJECTOR.VELOCITY = INJECTOR.VELOCITY / 12
840 '         OUTPUT RESULTS
850 LPRINT "THRUST COEFFICIENT = "; THRUST.COEFFICIENT
860 LPRINT "MOTOR EFFICIENCY ="; MOTOR.EFFICIENCY
870 LPRINT "THRUST ="; THRUST; "LBS"
880 LPRINT "BURN TIME ="; BURN.TIME; "SECONDS"
890 LPRINT "CHAMBER PRESSURE ="; CHAMBER.PRESSURE; "PSIA"
900 LPRINT "CHAMBER TEMPERATURE ="; 1.8 * (CHAMBER.TEMPERATURE - 273) + 32; "DEGREES
      F"
910 LPRINT "SPECIFIC IMPULSE ="; SPECIFIC.IMPULSE; "SECONDS"
920 LPRINT "CHARACTERISTIC EXHAUST VELOCITY ="; CSTAR; "FT/SECOND"
930 LPRINT "NOZZLE EXPANSION RATIO ="; EXPANSION.RATIO
940 LPRINT "MOTOR DIAMETER ="; CHAMBER.DIAMETER; "INCHES"
950 LPRINT "NOZZLE THROAT DIAMETER ="; NOZZLE.THROAT.DIAMETER; "INCHES"
960 LPRINT "NOZZLE EXIT DIAMETER ="; NOZZLE.EXIT.DIAMETER; "INCHES"
970 LPRINT "NOZZLE LENGTH ="; NOZZLE.LENGTH; "INCHES."
980 LPRINT "OXIDIZER FLOW RATE ="; OXIDIZER.FLOW.RATE; "LBS/SECOND"
990 LPRINT "FUEL FLOW RATE ="; FUEL.FLOW.RATE; "LBS/SECOND"
1000 LPRINT "TOTAL PROPELLANT FLOW RATE ="; TOTAL.PROPELLANT.FLOW.RATE; "LBS/SECOND"
1010 LPRINT "TOTAL OXIDIZER USED ="; OXIDIZER.FLOW.RATE * BURN.TIME; "POUNDS"
1020 LPRINT "TOTAL FUEL USED ="; FUEL.FLOW.RATE * BURN.TIME; "POUNDS"
1030 LPRINT "TOTAL PROPELLANTS USED ="; TOTAL.PROPELLANT.FLOW.RATE * BURN.TIME;
      "POUNDS"
1040 LPRINT "INJECTOR PRESSURE DROP ="; INJECTOR.DELTA.PRESSURE; "PSI"
1050 LPRINT "INJECTOR DIAMETER ="; INJECTOR.DIAMETER; "INCHES"
1060 LPRINT "INJECTOR VELOCITY ="; INJECTOR.VELOCITY; "FT/SECOND"
1070 LPRINT "FUEL GRAIN LENGTH ="; GRAIN.LENGTH; "INCHES"
1080 LPRINT "REGRESSION RATE COEFFICIENT ="; FUEL.REGRESSION.COEFFICIENT
1090 LPRINT "REGRESSION RATE EXPONENT ="; FUEL.REGRESSION.EXPONENT
1100 LPRINT "INITIAL PORT RADIUS ="; INITIAL.GRAIN.RADIUS; "INCHES"
1110 LPRINT "REGRESSION RATE ="; REGRESSION.RATE; "IN/SECOND"
1120 END
```

Sample Input file "MOTOR.DAT":

```
1.5
224.3
50
5.22
3038.3
500
5
.9
8
2.5
.8
100
46.5
.1
.8
.033
1
```

Sample output from test data using "MOTOR.DAT" as the input file:

```
INPUT DATA:
THRUST COEFFICIENT = 1.5
SPECIFIC IMPULSE = 224.3 SECONDS
THRUST = 50 LBS
EXPANSION RATIO = 5.22
CHAMBER TEMPERATURE = 3038.3 DEGREES KELVIN
CHAMBER PRESSURE = 500 PSIA
BURN TIME = 5 SECONDS
MOTOR EFFICIENCY = .9
0/F RATIO = 8
MOTOR DIAMETER = 2.5
INJECTOR DISCHARGE COEFFICIENT = .8
INJECTOR PRESSURE DROP = 100 PSI
OXIDIZER DENSITY = 46.5 LB/CU FT
REGRESSION RATE COEFFICIENT = .1
REGRESSION RATE EXPONENT = .8
FUEL DENSITY = .033 LBS/CU FT
FINAL CORE RADIUS = 1 INCHES


OUTPUT RESULTS:
THRUST COEFFICIENT =  1.5
MOTOR EFFICIENCY = .9
THRUST = 50 LBS
BURN TIME = 5 SECONDS
CHAMBER PRESSURE = 500 PSIA
CHAMBER TEMPERATURE = 5009.54 DEGREES F
SPECIFIC IMPULSE = 224.3 SECONDS
CHARACTERISTIC EXHAUST VELOCITY = 4811.085 FT/SECOND
NOZZLE EXPANSION RATIO = 5.22
MOTOR DIAMETER = 2.5 INCHES
NOZZLE THROAT DIAMETER = .307106 INCHES
NOZZLE EXIT DIAMETER = .701655 INCHES
NOZZLE LENGTH = 2.635342 INCHES.
OXIDIZER FLOW RATE = .2201637 LBS/SECOND
FUEL FLOW RATE = 2.752046E-02 LBS/SECOND
TOTAL PROPELLANT FLOW RATE = .2476842 LBS/SECOND
TOTAL OXIDIZER USED = 1.100818 POUNDS
TOTAL FUEL USED = .1376023 POUNDS
TOTAL PROPELLANTS USED = 1.238421 POUNDS
INJECTOR PRESSURE DROP = 100 PSI
INJECTOR DIAMETER = 9.299358E-02 INCHES
INJECTOR VELOCITY = 112.9308 FT/SECOND
FUEL GRAIN LENGTH = 10.70539 INCHES
REGRESSION RATE COEFFICIENT = .1
REGRESSION RATE EXPONENT = .8
INITIAL PORT RADIUS = .9372635 INCHES
REGRESSION RATE = 1.322812E-02 IN/SECOND
```

Correspondence

Flash Powder Output Testing: Weak Confinement, Issue 4, Winter 1996, p 5–14.

Society for the Preservation of the Memory of Alexander Graham Bell

1 V 97

Dear Dr. Kosanke,

The society would protest you (sic) misuse of the "Bell", named in honor of AG Bell, and the "deci-Bell" named in honor of his daughter "deci".

You claim to have measured the output of various flash/report comps in dB's. We doubt it!!! The dB being a ratio not a quantity! e.g., an increase in power from 1 to 2 watts represents a change of 3 dB. An increase from 1 000 to 2 000 watts is also an increase of 3 dB's!!! Sound level is measured in dBm's. That is; one deci-Bell is represented by one milliwatt of power dissipated in a 600 ohm resistance at 1 000 Hertz. Therefore, you could not have measured 100+ dBm's either. A hundred dBm noise would have been heard around the nation!!

Noise on the other hand is measured in either dBa's. (deci-Bells adjusted.) Or dBrn (deci-Bells reference noise. 90 dBrn = 1 dBm (1 milliwatt)). We here in the phone company use dBrnCO's. dB's reference noise - "C" message weighting (the same sound quality as you (sic) phone, i.e. cut's off at 3 200 Hz and less weighing for low frequencies) referenced to the milliwatt (0).

The Society does is not at this time requesting you publish corrections or retractions. We would, however, request your attention to the proper place for the unit(s) named for AG Bell and his daughter in future publications.

The Society

Authors' Response

Even though this comment was presented with humor and was unsigned, it deserves a serious response. Equation 1 in the paper is correct for measuring sound pressure levels (SPL), but it was not presented as a derivation from first principles. Because that omission may have caused some confusion, and because differing definitions may apply in other areas, such as with the phone system, a full derivation is presented here.

Universally, the bel (B) is a measure of a ratio of power levels (W), expressed as a logarithm,[1]

$$1) \quad \mathrm{B} = \log\left(\frac{W_1}{W_2}\right)$$

Similarly, a decibel (1/10 of a bel) is,

$$2) \quad \mathrm{dB} = 10 \bullet \log\left(\frac{W_1}{W_2}\right)$$

Often W_2 is some standard reference power level and could be represented as W_0. For pressures (P), power is proportional to pressure squared[2-4], thus

$$3) \quad \mathrm{dB} = 10 \bullet \log\left(\frac{P}{P_0}\right)^2 \quad \text{or}$$

$$4) \quad \mathrm{dB} = -20 \log P_0 + 20 \log P$$

For sound pressure levels, the standard reference pressure (P_0) is 0.0002 dyn/cm^2 [r.m.s. (root mean square) at 1000 Hz], which corresponds to 2.9×10^{-9} psi. By substitution and carrying out the mathematics, equation 4 becomes,

$$5) \quad \mathrm{dB} = 170.8 + 20 \log P$$

which is equation 1 from the subject article.

There is one fine point remaining to be addressed. To be fully correct within this derivation, P in equation 5 should be r.m.s. pressure and not peak pressure. However, r.m.s. effectively has no meaning for an impulse sound

which is a single pressure event (is not repetitive) and has varying positive and negative phase durations, depending on measurement geometry and source type. Accordingly, it is customary to use peak pressure for impulse sounds (blast waves),[5,6] as was done in this article.

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4) *Encyclopedia of Physics* Second ed., VCH Publishers, 1991, p 22.

5) K.D. Kryter, *The Effects of Noise on Man*, Academic Press, 1970, p 187.

6) P.W. Cooper, *Explosives Engineering*, VCH Publishers, 1996, p 420.

Ken Kosanke

Flash Powder Output Testing: Weak Confinement, Issue 4, Winter 1996, p 5–14.

Comment from Fred Ryan

I enjoyed your article on "Flash Powder Output Testing: Weak Confinement", that appeared in Issue 4 of the *Journal of Pyrotechnics*. It is a welcome quantitative study on fireworks effects. I would like to make one suggestion however. The measurements were performed at distances very close to the explosions. The distance at which the typical observer is located is much greater than the 1.9 meters used in the testing. A distance of 100 meters or more would be more typical of the distance at which the fireworks observer would be located. While relative strength measurements can be made at close distances, I wonder how well they relate to the volume of the blast perceived by the fireworks observer at a much greater distance? For example, a frequency analysis of the positive pressure wave was shown in Figure 2 yields frequency components far above 1000 Hz. The attenuation of such high frequency components in air would change the wave form considerably at a distance of 100 meters. Since the attenuation versus frequency varies with temperature and humidity, I have chosen an arbitrary temperature of 20 ºC and a relative humidity of 30%. Under those conditions the relative attenuations at 100 meters of a few selected frequencies are:[1]

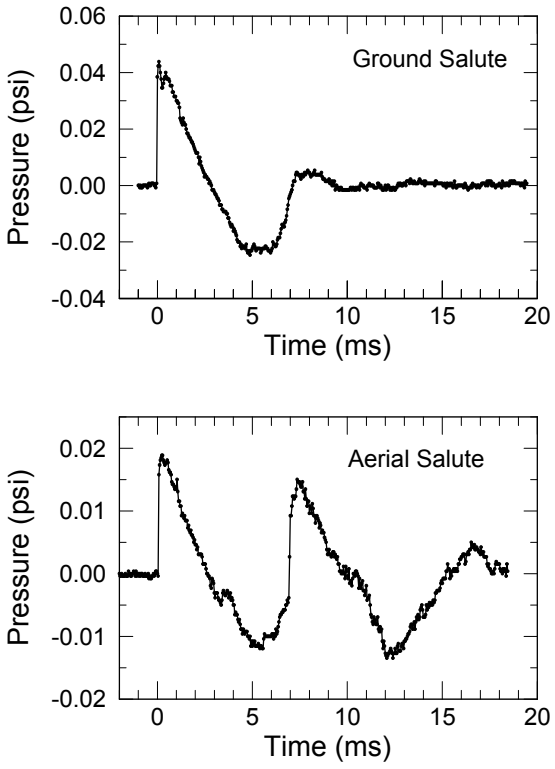
Frequency (Hz)	Attenuation (dB/100 meters)
250	0.08
1,000	0.52
4,000	4.5
10,000	21

The blast wave form that would reach the fireworks observer at 100 meters would therefore differ from that shown in Figure 2. We have performed some wave form measurements on flash salutes at 100 meters. The wave forms that we measured showed positive and negative wave shapes that were almost identical in amplitude and duration. The impulse resembled the single cycle of a sine wave of approximately 250 Hz. While our salutes differed considerably in construction from your flash tests, I suspect that your measurements at 100 meters would be similar to ours. I believe that such measurements would be of interest. Converting such measurements into the subjective "sound" on the observer is, of course, another matter entirely!

Reference 1: *American Institute of Physics Handbook*, Third ed., McGraw Hill, 1982, Chapter 3 (Acoustics), p 3–79 to 3–83.

Author's Reply

Thanks for the input about the flash powder testing. You certainly are correct about there being an effect of distance. However, so long as the waves are supersonic, they do maintain the high frequency components that produce the near instantaneous rise that is characteristic of a shock wave. Enclosed are two blast wave traces for 3" salutes at a distance of about 360 feet. The duration of positive phase has increased from 1 ms, at close range, to about 3 ms. Also, the aerial salute gives rise to a double peak resulting from a reflection off the ground.



The trace for a ground salute was taken this past year at the Western Winter Blast during an experiment to discover the effect of sulfur in flash powder with respect to tonal quality. The data is being compared to the responses of a group of human subjects who rated the salutes' loudness, tonal quality, and chest thump. We are in the process of writing up the results for publication and are planning for significantly expanded testing next year.

Sincerely,

Ken Kosanke

Further Comment from Fred Ryan

Ken states that as long as the pressure waves are supersonic that they produce the near instantaneous initial pressure rise as shown in the accompanying graphs. I think that a literature reference of this should be given if the data are to be published. It would also be very desirable to prove that at the distance at which these measurements were made that the pressure waves were in fact supersonic. Two pressure gauges spaced apart a given distance from the salutes (say, one at 100 meters and one at 101 meters) could yield a velocity of propagation figure. I'm not saying that the wave forms shown are not really representative of supersonic waves, it's just that a method of triggering the wave forms from the incidence of the first pressure wave striking the gauge can lose some of the early information on the wave shape, resulting in the sharp rises shown. How was the storage scope triggered? In the second graph two pressure wave forms are shown, the first (direct) wave shows a very fast rise of pressure with time, while the second (ground reflected) wave does not. Does this mean that the reflected wave, even though it is following right on the heels of the direct wave is sonic, while the direct wave is supersonic? If that is true then either the reflected wave has just made the transition from supersonic to sonic or the two wave forms should be much more separated in time of arrival. My guess is that both wave forms are traveling at the velocity of sound and that some of the earlier wave form of the direct wave has been lost due to triggering or another electronic glitch. What do you think?

Fred Ryan

Authors' Second Response

Thanks again, this time for your follow-up comment.

The process whereby any sufficiently powerful pressure event produces a shock wave, sometimes termed "shocking up", is described by Kinney and Graham [*Explosive Shocks in Air*, Springer-Verlag, 1985, pp 88–90]. As they describe it, the development of the shock wave, with its essentially instantaneous leading edge pressure rise (see Figure 1 in the article), is a result of the higher pressure part of the wave tending to catch up with any lower pressure parts of the wave preceding it. This is because for the brief duration of the pressure wave it is essentially an adiabatic system. Thus the higher pressure part of the wave is at a higher temperature (e.g., consider the ideal gas law); which means the local speed of sound is greater in the higher pressure part of the wave; which means the higher pressure part of the wave is traveling faster and catches up with any preceding lower pressure parts of the blast wave. So long as the propagation of the blast wave remains more than slightly supersonic, if any process acts to

degrade the steepness of the leading edge, then the same shocking up process must again act to restore it.

You suggest measuring the speed of a salute's shock wave at a distance, to determine whether is remains supersonic. This can easily be done as you suggest, and we may do so one of these days. However, by much the same logic as suggested above and your comment about the degradation of high frequency components of the blast wave form, it would seem that whenever a pressure wave is observed with its shock front intact, it must still be progressing supersonically.

The digital oscilloscopes that we use, and I suspect this is true for essentially all digital scopes, digitizes the input signal and stores it in a buffer on a continuous basis. Once triggered, the buffered data is transferred to a storage register and displayed. (At slower digitizing rates, the data is displayed as it is input, and it scrolls across the display of the scope.) This allows what is called "pre-triggering", which accurately captures data occurring prior to the triggering event, which in this case was the arrival of the blast wave itself. Accordingly, for the graphs presented above and in the article, the essentially instantaneous rise is real and is not an artifact of the measuring (triggering) process.

You commented on the fact that the second of two blast waves in the second graph above, does not appear to have the same sharp rise as the first blast wave. That is true, but remember that second blast wave is superimposed over the end of the negative phase of the first blast wave. Also the reflecting surface was uneven and there were a few large rocks on the surface (i.e., it was far less than ideal). Thus it is not necessarily an indication that the reflected blast is no longer traveling supersonically.

Events Calendar

Pyrotechnics

Introduction to Explosives and Explosive Technology and Modeling

September 15–19, 1997, Santa Fe, NM USA

Contact: Computational Mechanics Associates
PO Box 11314
Baltimore, MD 21239, USA

Phone: 410-532-3260 [in USA 800-441-5591]
FAX: 410-532-3261

23rd International Pyrotechnics Seminar

September 30–October 4, 1997, Tsukuba, Japan

Contact: Prof. Tadao Yoshida
College of Engineering of Hosei University
3–7–2 Kajino–cho, Koganei–shi
Tokyo 184, Japan

Phone: 81-423-87-6132
FAX: 81-423-87-6381

The International Autumn Seminar on Propellants, Explosives, and Pyrotechnics

October 8–10, 1997, Shenzhen, China

Contact: Prof. Changgen Feng
Mechanics and Engineering Dept.
Beijing Institute of Technology
PO Box 327
Beijing 100081, China

Phone: 86-10-6891-2764
FAX: 86-10-6842-2889
e-mail: cgfeng@public.east.cn.net

Pyrotechnic Chemistry Course — UK – 1998

Spring 1998 -- Date and Place in the United Kingdom not determined at this time.

Contact: Ken Kosanke, PyroLabs
1775 Blair Road, Whitewater, CO 81527, USA

Phone: 970-245-0692
FAX: 970-245-0692
e-mail: bonnie@jpyro.com

Fireworks

Benson & Hedges International Fireworks Competition in Montreal, Canada – 1997

Dates and Competitors:

June 7 Igual, Spain
June 14 Brezac, France
June 21 JNS, Holland
June 28 Gunter Vogler, Austria
July 5 Weco, Germany
July 9 IPON, Italy
July 13 Fiatlux, Canada
July 16 Rozzi, USA
July 20 Closing by Panzera of Spain

Contact: AMARC
Île Notre-Dame
Montreal, Quebec H3C 1A9, Canada
Phone: 514-872-6241
FAX: 514-872-8711

Symphony of Fire – Fireworks Displays

Toronto, Canada – 1997 Schedule:

June 14 Western Enterprises, Inc. USA
June 21 Pirotecnia Minhota, Portugal
June 25 A. Caballer, S.A., Spain
June 28 Beijing Fwks Art Co.,China
July 1 NANNA Fireworks SRL, Italy
July 5 Closing Show

Vancouver, Canada – 1997 Schedule:

July 26 Pirotechnia R. Caballer, SA, Spain
July 30 Beijing Fwks. Art Co., China
Aug. 2 Pyro 2000, United Kingdom
Aug. 6 Closing

Contact: Frank Furtado
3054 Lacombe
Montreal, Quebec H3T 1L4, Canada
Phone: 514-866-3335
FAX: 514-398-9287

Pyrotechnics Guild International Conv.

August 10–15, 1997, Cedar Rapids, IA, USA

Contact: Monte Whitlock, Chairman
1620 Twin Valley Drive
Solon, IA 52333-9320, USA
Phone: 319-848-4075
FAX: 319-848-4282
e-mail: montedw@aol.com

High Power Rocketry

LDRS XVI

Aug. 7–10, Hartsell, CO, USA

Contact: Dario Brisighella
477 S. Kingston Circle
Aurora, CO 80012 USA
Phone: 303-364-8134
e-mail: 75463.2363@compuserve.com

Model Rocketry

NARAM–39

July 26–August 1, 1997, Tucson, AZ, USA

Contact: Steve Lubliner
9968 E. Domenic Lane
Tucson, AZ 85730, USA
Phone: 520-296-1689
e-mail: 103056.621@compuserve.com

Thrust – UK Midlands Rocket Club

June 8, July 20, Sept. 21 and Oct. 12 1997

Contact: Ian Holtham
Phone: 44-1827-310-486
e-mail: ianh@bidesign.demon.co.uk

Blazing Archer I

August 23–24, 1997, Petewawa, ONT, Canada

Contact: Glen MacGillivray or Glen Hillier
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