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Some Aspects of Pyrotechnic Modeling

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ABSTRACT

Several aspects of pyrotechnic devices used to produce smoke, flash and sound are discussed quantitatively. The main aim of this paper is to demonstrate economical techniques to tailor pyrotechnic formulations to meet specific needs. It is seen that the cloud size is independent of the charge weight in the range of 2-80 gm, a theoretical result that is verified by experimental data. The noise is found to be in good agreement with experimental data, especially after allowance is made for absorption in the atmosphere. Several formulations are tested and the results are presented.

Tailoring of pyrotechnics to achieve specific effects of cloud size, shape and longevity is discussed. Applications of pyrotechnics for gas generation purposes are also mentioned. It is seen that these studies complement more extensive testing; mutually, they introduce great economy and provide insight not possible with empirical approaches.

1. INTRODUCTION

Pyrotechnic devices are finding increasing use not only in the conventional fields of ignitors, explosives and store separation, but also in the art of simulations togreatly economize training costs without compromising safety. The compact, inexpensive, reliable, solid 'powders' provide a ready source of gases upon ignition. These gas generation applications include actuation of simple devices and those needing high-pressure, expendable gas sources in the field. In the latter case, it is frequently desirable to tailor the product temperature to be low (< 1000°K). Also, in the familiar field of fireworks, the need for innovative, spectacular displays is ever growing and

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represents a not insignificant fraction of pyrotechnic use. Considering the importance, extensive use, mission criticality, and enormous potential for future uses, it is surprising that simple analytical modeling techniques are not readily available to tailor devices to specific needs. Many of the highly successful designs seem to be based on experience, educated guesses, and empiricism. While the success of these approaches is attested by the working devices, the economy of design is open to question. Besides, when newer applications arise, these empirical techniques show their limitations. For example, simple questions such as "how much more charge to use to increase the cloud size by 20 per cent or what ingredient to use to make the flash 30 per cent brighter" frequently take extensive testing to answer.

It was felt worthwhile to explore the possibility of developing a simple framework for modeling pyrotechnics. Ideally, one would like to generate an accurate closed-form solution where the effects on smoke/cloud, flash, noise, and other features can all be easily interpreted quantitatively. Such a solution will be able to answer questions such as those posed above. Considering the complexity of the problem and the multitude of variables involved, we may have to settle for less. That is not to say that the less-than-ideal solutions will not be useful. Even a simple solution, indicating trends, can be an improvement over empirical techniques. Gradually, we can build upon the initial solution by adding more and more complexities. At this stage, experimental data provide a valuable means of verification and feedback to the theory to improve the modeling. The modeling will not replace the experiments. It is hoped to reduce the number of trial-and-error tests. A factor of two reduction will be worth the effort; a factor of ten seems possible.

This paper outlines a simple modeling procedure to evaluate the smoke/cloud size and the sound generated by pyrotechnics in the 2-80 gm range. Both pyrotechnics in this range and much larger ones (up to 22 kg) are tested and the theory verified. The theory predicts that, in the pyrotechnics used, the cloud size ought to be reasonably independent of the charge weight. This is verified by the experiments. The theory says that the cloud size ought to be proportional to the product particle density – again, an observation consistent with experiments. The theory is not developed in detail, but the salient points are quoted from a recent paper. Based on the concept of expected cloud density, applications to larger devices are discussed. Special ingredients are tested to verify the model. Theoretical performance data are generated to evolve cool pyrotechnics for gas generators. The continuing problems are mentioned and an interim summary is presented in Section 6.

2. THE MODEL

Consider a spherically symmetric assembly of an oxidizer/fuel formulation ignited at its centre. If the charge is sufficiently small (typically under 100 gm or under 50 ml in volume), the combustion is complete without dispersion of the ingredients. High-speed motion pictures reveal that the ignition/combustion is complete, typically, in 10-30 ms. The reactants are converted to products; the chemical energy is essentially imparted to the products as kinetic energy of the particles, while some energy is released as electromagnetic radiation (flash, for example) and in doing pV work on the expanding gases. We will, for the moment, concentrate on the kinetic energy of the product particles. It is of interest to determine the size of the cloud at the end of the particle travel.

In the Al-$Mg/KClO_4$ family of ingredients, the product distributions, represented as an 'average' from the equilibrium and frozen assumptions, indicate theoretically the presence of MgO, Al, $AlCl$, Al_2O, Al_2O_3, K, KCl, and occasionally, AlO, $AlOCl$, and Cl as the key species. The 'chamber' temperature has varied from 4107 to 5339°K as the 'chamber' pressure varied from 500 to 5000 psia. These numbers cover a small range of stoichiometry, too.

The products are seen to form two families, one is the aluminium oxide family (includes Mg family, too) and the other is the potassium salts family. Hence, based on extensive rocket studies, it is reasonable to suppose that the aluminium oxide family has a product particle size of 10 to 20μ. The potassium salt family, assuming that a simple nucleation process dominates, should have a particle size in the vicinity of 0.1μ. Indirect support is lent to this assumption from the fact that the cloud is experimentally seen to obscure (absorb) light, indicating particle size $\leqslant$ light wavelengths, i.e., 0.3 to 0.6μ. Thus, it is clear that the aluminium oxide family contributes little to the light absorption.

2.1 Analysis

The model considered for analysis is as follows. Within a very short time (short compared to the time of cloud formation or spread), the metal $+KClO_4$ is converted chemically to oxides and potassium salts. (The formation of these products could be continuous throughout the expansion but is not considered at the present time). The chemical energy of the products is converted to the kinetic energy of the product particles (by some process akin to the nozzle expansion in rockets). The product particles travel in still air, and the cloud expands. The kinetic energy of the particles is dissipated due to viscous drag, and the particles decelerate and stop. The distance traversed by the time all of the kinetic energy is dissipated is the radius R of the cloud. Nonviscous dissipative processes, such as conductive and convective heat loss and radiation from particles, are not considered at the present time. Hence, the basic formulation uses

$$\begin{matrix}\text{Chemical Energy} \\ \text{of the Charge}\end{matrix} = \begin{matrix}\text{Kinetic Energy} \\ \text{of the Particles} \\ \text{of the Cloud}\end{matrix} = \begin{matrix}\text{Energy Dissipated in} \\ \text{Overcoming Viscous} \\ \text{Losses in Travel}\end{matrix}$$

Each term has to be evaluated in turn. Needed property values are read from the CRC handbook (Physics and Chemistry), 47th edition, and the JANNAF thermochemical tables:

	Al, Al_2O_3 family	*KCl, K family*
Specific Heat (cal/gm°C)	0.32 (liquid)	0.23 (liquid) 0.13 (gas)
Density (gm/cm^3)	3.7	1.984 & 0.862 *Use* 1.42

It is clear that the behaviour of the 20μ Al_2O_3 weighing 3.7 gm/cm^3 will be very different from the 0.1μ *KCl* weighing 0.862 gm/cm^3, and these two are treated separately in the cloud expansion. However, assuming thermal equilibrium at the start, the temperature is considered to be equal for the two families of species in order to evaluate the initial enthalpy of the products; for this purpose, an initial average specific heat of 0.25 cal/gm°C is used for the products.

2.1.1 *Initial Product Velocity*

*(a) Assumption of Full Temperature Drop to 300°*K from 4300°K

This represents the absolute limit for the velocity

$$\tfrac{1}{2}\, m\, v^2 = m \,\Delta\, h$$

Assuming thermally and calorically perfect products (enthalpy, $\Delta\, h = C_p\, \Delta\, T$),

$$\tfrac{1}{2}\, m\, v^2 = m C_p\, \Delta\, T$$

$$v = \sqrt{C_p\, \Delta\, T . 2}$$

The acceleration due to gravity g_0 and the mechanical equivalent of heat J are needed to keep track of the units properly. Hence,

$$v = \sqrt{2 C_p\, \Delta T\, g_0\, J}$$

$$= \sqrt{2 \times 0.25 \times 4000 \times 32.2 \times 1400}$$

$$v_i = 9495 \text{ ft/sec} = 28{,}500 \text{ cm/sec}$$

(b) Assumption of Adiabatic Expansion from 500 to 14.7 psia

The available temperature drop is now evaluated through the adiabatic equation:

$$\frac{T_e}{T_c} = \left[\frac{P_e}{P_c}\right]^{(\gamma-1)/\gamma} \text{, (assuming } \gamma = 1.3\text{)}$$

or

$$T_e = T_c \left[\frac{14.7}{500}\right]^{0.3/1.3}$$

$= 4300 \times 0.44 = 1906°K$

or

$$\Delta T = T_c - T_e = 4300 - 1906 = 2394°K$$

Therefore $v_2 = \sqrt{2 \times 0.25 \times 2394 \times 32.2 \times 1400}$

$v_2 = 7346$ ft/sec $= 22{,}000$ cm/sec

Such initial velocities indicate hypersonic conditions in addition to the very low Reynolds numbers. Recognizing that the Knudsen number is approximately the ratio of Mach number to the Reynolds number, it may very well be that continuum mechanics may not be adequate to handle this problem. It is, however, recognized that these extremely high particle speeds do not last long because of the tremendous viscous dissipation and, hence, the continuum laws may be valid within a few centimeters of travel.

2.1.2 *Kinetic Energy of Particles:*

The kinetic energy consists of the v^2_1 (or v^2_2) plus the kinetic energy due to the spin of the cartridge (≈12,000 rpm or 200 rps). Assuming a cartridge diameter of 1 cm and an even distribution of mass within it, the mean tangential velocity is thus seen to be approximately $\pi \bar{d} \omega = 600$ cm/sec at 12,000 rpm. This is negligible compared to the explosion velocity.

2.1.3 *Basic Equation for Cloud Radius R:*

$$\tfrac{1}{2}mv^2 = \int_0^R \bar{F}\,dr \qquad \text{[recall that } m = w/g_0\text{]}$$

where m is the mass of each particle, v is the initial velocity, F is the instantaneous viscous drag at any location r from the centre of the cloud, and R is the ultimate radius where the velocity of the products is zero.

2.1.4 *Drag Law :*

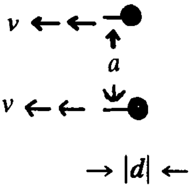
In this section, μ is the dynamic viscosity of air (gm/cm sec or lbm/ft sec), d is the diameter of the particles (cm or ft), and v is the relative velocity between particles and air (cm/sec or ft/sec).

Stokes Law Valid for Simple Particles in the Reynolds Number (R) Range 0.1 to 2 :

$$\bar{F} = 3\pi\mu v d$$

Corrected Stokes Law for Multiple Particles :

$$\bar{F} = 3\pi\mu v d\lambda'$$



$$\frac{a}{2d} = 1 \rightarrow \lambda' = 0.645$$

$$\frac{a}{2d} \rightarrow \infty \rightarrow \lambda' = 1$$

A Transition Law Valid for 10 < R < 2000

$$C_D \equiv \frac{\bar{F}}{\frac{1}{2}\rho v^2 \; \frac{\pi d^2}{4}} \propto 10.77R{-}0.43$$

2.1.5 *Cloud Radius*

Al, Al_2O_3 family	*K, KCl family*
$d \simeq 20\mu$	$d \simeq 0.1\mu$
$\mu/\rho_{air} = \nu_{air} = 1.6\times10^{-4}ft^2/sec$	$\nu_{air} = 1.6\times10^{-4}ft^2/sec$
$v_{initial} = 9495$ ft/sec (v_1)	$v_1 = 9459$ ft/sec)
$= 7346$ ft/sec (v_2)	$v_2 = 7346$ ft/sec
$R_1 = dv_1/\nu = 3956$	$R_1 = 20$
$R_2 = dv_2/\nu = 3061$	$R_2 = 15$

It is seen that the *Al* family particles may start in the laminar regime but quickly enter the Stokes regime. The *K, KCl* family particles are always in the Stokes-Oseen regime.

(a) *Stokes Drag Law :*

This is not strictly applicable but will demonstrate trends. Assuming a *constant* average drag, of F

$$\int_0^R \bar{F}dr = \bar{F}.R = \tfrac{1}{2}\, mv^2$$

$$R = \frac{mv^2}{2F} - \frac{mv^2}{2.3\pi\mu\, vd} = \frac{mv}{6\pi\mu d}$$

Recognize that the mass of a product particle is

$$m = \frac{\frac{\pi}{6}d^3\rho_p}{g_0}$$ where ρ_p is the particle density

Therefore $$R = \frac{d^2\rho_p}{36\,\mu\, g_0}$$

Before computing numbers, it is interesting to note the following :

(i) The total mass of the charge does not influence the R.

(ii) The cloud radius is directly proportional to the density of the product particles.

(iii) The cloud radius is proportional to the square of the product particle diameter.

(iv) The cloud radius is inversely proportional to the viscosity of the ambient air.

(v) The cloud radius is proportional to the initial velocity of the products which, in turn, relates to the energy content of the charge (reactants) as the square root.

Fig. 1 shows a typical firing and Fig. 2 compares the theory with experimental data. In many applications, it is not sufficient to confirm the near constancy of the cloud size; it is desired to increase the size. Here, the analysis can help in indicating that ρ_p directly influences the cloud radius. Thus, any ingredient that results in a high-density product (without increasing the particle size) would be expected to increase the cloud size. Thus, it comes as no surprise that zinc and titanium have both indicated larger cloud sizes, even when added in small concentrations. A series of tests was performed and the results are shown in Table 1. Some of the qualitative observations are summarized here:

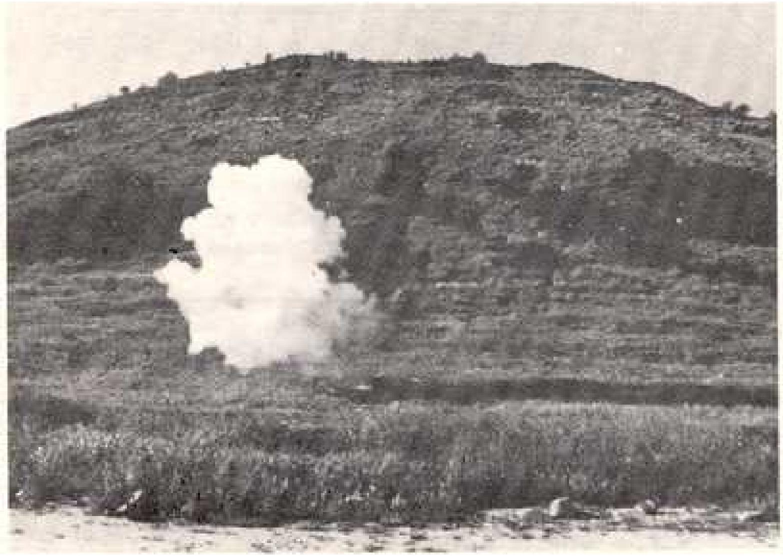


Figure 1. Typical firing of a 40-gm pyro charge. The markings on the poles are 1 m long.

1. All of the formulations were successfully ignited and performed well.
2. The overall cloud size was approximately the same at 2-5 seconds after ignition. In addition, it appeared that the sizes were not too much larger than those from the earlier 2-gm batches. This is very encouraging for the theoretical developments.

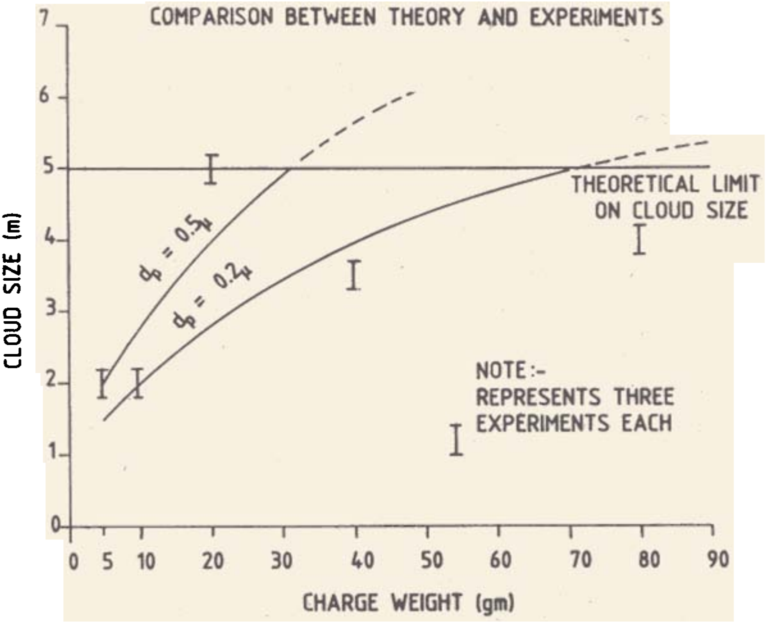


Figure 2. Cloud size predictions and comparisons with experiments.

Table 1. Some compositions of test charges and results.

No.	Composition (all in gm)	Flash size at ignition (m)	Cloud size 0.2-0.5 sec (m)	Comments
C1(a)	Stoichiometric Al + KP	Not seen	1	Small, light clouds
C1(b)	Stoichiometric Al + KP	Not seen	1	
C2(a)	0.9 KP + 0.9 Al	1	1.3	Bright white flash;
C2(b)	0.9 KP + 0.9 Al	0.6	1.3	dense white clouds
2(a)	0.8 KP + 0.8 Al + 0.2 Zn	0.5	1.5	White cloud
2(b)	0.8 KP + 0.8 Al + 0.2 Zn	0.5	0.8	split cloud
6(a)	0.8 KP + 0.8 Al + 0.2 $BaNO_3$	1	1	Bright flash
6(b)	0.8 KP + 0.8 Al + 0.2 $BaNO_3$	1	1	split cloud
8(a)	0.8 KP + 0.8 Al + 0.2 $NaNO_3$	0.8	1	Thin bluish clouds
8(b)	0.8 KP + 0.8 Al + 0.2 $NaNO_3$	0.6	1	
9(a)	0.8 KP + 0.8 Al + 0.2 CaAC	Not seen	0.6	Dull thin clouds
9(b)	0.8 KP + 0.8 Al + 0.2 CaAC	Not seen	0.5	
10(a)	0.8 KP + 0.8 Al + 0.2 Ti	1	1.4	Bright flash and dense
10(b)	0.8 KP + 0.7 Al + 0.3 Ti	0.6	1.5	white clouds; clouds linger around and do not spread quickly

3. The clouds, however, were more full; that is, they looked much more dense than before.

4 Zinc in the formulations does not appear to influence the cloud size to any significant degree (but does increase the cloud size a little).

Titanium, when placed outside the core charge of *Al+KP,* gave spectacular sparkles flying in all directions.

6. Titanium, when mixed with the core charge *Al+KP* (with or without zinc), did not give any sparkles but generated a very dense, bluish white cloud.

One special charge was fired in addition to these fourteen. A 5-gm cue was prepared without the core of *Al+KP.* The entire charge consisted of *Zn+Ti+KP* only. This cue was not very spectacular. The cloud generated was very heavy and settled near the ground. In addition, this cloud did not disperse readily.

8 The noise levels were surprisingly lower than those produced by the earlier 2-gm batches. This could be due to the lower bursting pressures of these larger capsules.

9 The debris from these firings clearly indicate melting of the polycarbonate tube. The larger ones were found approximately 25 feet from the firing spot, and the smaller ones were typically at 15 feet.

3. COOL GAS GENERATORS

Pyrodevices are used as gas generators. The thermochemical calculations with sodium bicarbonate as the coolant are shown in Table 2 (control AP/PBAN in Table 2a compares the cool propellant in Table 2b). It is seen that substantially cooled gases are possible with this simple addition.

4. NOISE GENERATION

The bang is related simply to pressure wave propagation in air as

$$\frac{p_4}{p_1} = \frac{p_2}{p_1}\left[\frac{(\gamma_4 - 1)\,\frac{a_1}{a_4}\left[\frac{p_2}{p_1} - 1\right]}{\sqrt{2\gamma_1}\,\sqrt{2\gamma_1 + (\gamma_1 + 1)\left[\frac{p_2}{p_1} - 1\right]}}\right]^{\frac{\gamma_4}{\gamma_4 -}}$$

where

p_1 is the ambient pressure

p_4 is the shell burst pressure

p_2 is the "bang" or sound pressure

Obviously, p_2/p_1, the pressure ratio resulting in the bang, is implicit and can be solved

Table 2a. Thermochemical performance of the control formulation control : 20% PBAN, 80% AP

THERMODYNAMIC EQUILIBRIUM COMBUSTION PROPERTIES AT ASSIGNED PRESSURES

	CHEMICAL FORMULA				WT FRACTION (SEE NOTE)	ENERGY CAL/MOL	STATE	TEMP. DEG K	DENSITY G/CC
OXIDANT	N 1.00000	H 4.00000	CL 1.30000	O 4.00000	1.00000	−70690.000	S	298.15	0.0000
FUEL	C 6.47600	H 9.07700	O .62800	N .21800	1.00000	−16000.000	S	298.15	0.0000

O/F = 4.0000 PERCENT FUEL = 20.0000 EQUIVALENCE RATIO = 1.5222 REACTANT DENSITY = 0.0000

THERMODYNAMIC PROPERTIES

P, ATM	1.0000	2.0000	3.0000	4.0000	5.0000	6.0000	6.0000	7.0000	8.0000	.9.0000	10.000	75.000
T,DEG K	2493	2517	2530	2538	2543	2548	2548	2551	2554	2557	2559	2587
PHO, G/CC	1.1349−4	2.2530−4	3.3669−4	4.4783−4	5.5881−4	6.6969−4	6.6969−4	7.8046−4	8.9117−4	1.0018−3	1.1124−3	8.2733−3
H, CAL/G	−513.3	−513.3	−513.3	−513.3	−513.3	−513.3	−513.3	−513.3	−513.3	−513.3	−513.3	−513.3
S, CAL/(G)(K)	2.8106	2.7513	2.7167	2.6922	2.6732	2.6576	2.6576	2.6445	2.6331	2.6231	2.6141	2.4430
M MOL WT	23.218	23.269	23.295	23.311	23.324	23.333.	23.333	23.340	23.347	23.352	23.356	23.417
(DL V/DLP)T	−1.00521	−1.00410	−1.00354	−1.00317	−1.00291	−1.00271	−1.00271	−1.00256	−1.00241	−1.00230	1.00220	−1.00092
(DL V/DLT) P	1.1210	1.0945	1.0811	1.0726	1.0663	1.0616	1.0616	1.0578	1.0547	1.0521	1.0498	1.0203
CP, CAL/(G)(K)	.6898	6347	.6073	.5899	.5776	.5680	.5680	.5605	.5543	.5491	.5446	.4867
GAMMA (S)	1.1775	1.1863	1.1914	1.1948	1.1974	1.1994	1.1994	1.2011	1.2026	1.2037	1.2048	1.2204
SON VEL, M/SEC	1025.3	1033.0	1037.1	1039.9	1041.9	1043.5	1043.5	1044.8	1045.8	1046.8	1047.6	1058.8

MOLE FRACTIONS

CO	.23129	.23203	.23240	.23263	.23280	.23293	.23293	.23304	.23312	.23320	.23326	.23407
CO_2	.06947	.06939	.066936	.06934	.06933	.06932	.06932	.06931	.06931	.06930	.06930	.06926
CL	.00657	.00521	.00451	.00405	.00372	.00347	.00347	.00326	.00309	.00295	.00283	.00117
CL_2	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00001	.00001	.00001	.00001	.00001
H	.00959	.00753	.00649	.00581	.00533	.00495	.00495	.00466	.00441	.00420	.00402	.00165
HCL	.15152	.15322	.15410	.15467	.15508	.15540	.15540	.15565	.15587	.15605	.15620	.15826
H_2	.15635	.15630	.15627	.15625	.15624	.15623	.15623	.15623	.15622	.15621	.15621	.15614
H_2O	.28706	.28878	.28966	.29024	.29065	.29097	.29097	.29123	.29144	.29162	.29177	.29384
NH_3	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00001
NO	.00018	.00015	.00013	.00012	.00011	.00011	.00011	.00010	.00010	.00009	.00009	.00004
N_2	.08402	.08422	.08432	.08439	.08444	.08447	.08447	.08450	.08453	.08455	.08457	.08480
O	.00015	.00009	.00007	.00006	.00005	.00004	.00004	.00004	.00003	.00003	.00003	.00000
OH	.00370	.00301	.00263	.00238	.00220	.00206	.00206	.00195	.00185	.00177	.00170	.00072
O_2	.00011	.00007	.00005	.00004	.00004	.00003	.00003	.00003	.00003	.00002	.00002	.00000

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.50000E−05 FOR ALL ASSIGNED CONDITIONS

C(%)	C	CCL	CCL_2	CCL_3	CCL_4	CH	CH_2	CH_2O	CH_3
CH_3CL	CH_4	CN	CNN	CN_2	COCL	$COCL_2$	C_2	C_2CL_2	C_2H
C_2H_2	C_2H_4	C_2H_6	C_2N	C_2N_2	C_2O	C_3	C_3O_2	C_4	C_4N_2
C_5	CLCN	CLO	CLO_2	CL_2O	HCN	HCO	HNCO	HNO	HNO_2
HNO_3	HO_2	H_2N_2	$H_2O(S)$	$H_2O(L)$	H_2O_2	N	NCO	NH	NH_2
NOCL	NO_2	NO_2CL	NO_3	N_2H_4	N_2O	N_2O_4	N_2O_5	N_3	O_3

NOTE. Weight fraction of fuel in total fuels and of oxidant in total oxidants.

Table 2b. Thermochemical performance of the cooled formulation AP/PBAN + 74% Purple K

THERMODYNAMIC EQUILIBRIUM COMBUSTION PROPERTIES AT ASSIGNED PRESSURES

	CHEMICAL FORMULA				WT FRACTION (SEE NOTE)	ENERGY CAL/MOL	STATE	TEMP DEG K	DENSITY G/CC
OXIDANT	N 1.00000	H 4.00000	CL 1.00000	O 4.00000	.22222	−70690.000	S	298.15	0.0000
FUEL	C 6.47600	H 9.02700	D .62800	N .21800	1.00000	−16000.000	S	298.15	0.0000
OXIDANT	K 1.00000	H 1.00000	C 1.00000	O 3.00000	.55556	−227250.000	S	298.15	0.0000
OXIDANT	K 1.00000	H 1.00000	C 1.00000	O 3.00000	.11111	−227250.000	S	298.15	0.0000
OXIDANT	K 1.00000	H 1.00000	C 1.00000	O 3.00000	.11111	−227250.000	S	298.15	0.0000

O/F = 18.0000 PERCENT FUEL = 5.2632 EQUIVALENCE RATIO = 1.1439 REACTANT DENSITY = 0.0000

THERMODYNAMIC PROPERTIES												
P, ATM	1.0000	2.0000	3.0000	4.0000	5.0000	6.0000	6.0000	7.0000	8.0000	9.0000	10.000	75.000
T, DEG K	928	930	932	935	938	941	943	943	945	948	950	997
RHD, G/CC	7.0745−4	1.4138−3	2.1186−3	3.5237−3	3.5237−3	4.2244−3	4.2244−3	4.9241−3	5.6228	6.3208−3	7.0160−3	5.1830−2
H, CAL/G	−1807.6	−1807.6	−1807.6	−1807.6	−1807.6	−1807.6	−1807.6	−1807.6	−1807.6	−1807.6	1−1807.6	−1807.6
S, CAL/(G))K)	1.3544	1.3288	1.3139	1.3033	1.2952	1.2885	1.2885	1.2828	1.2780	1.2737	1.2699	1.1978
M, MOL WT	53.857	53.934	54.033	54.139	54.244	54.344	54.344	54.439	54.527	54.610	54.688	56.534
(DL V/DLP)T	−1.00110	−1.00368	−1.00673	−1.00963	−1.01216	−1.01431	−1.01431	−1.01611	−1.01763	−1.01892	−1.02001	·1.02749
(DL V/DLT)P	1.0172	1.0566	1.1032	1.1472	1.1856	1.2179	1.2179	1.2450	1.2677	1.2868	1.3030	1.4041
CP, CAL/(G)(K)	.3776	.3994	.4253	.4495	.4704	.4878	.4878	.5022	.5142	.5241	.5324	.5714
GAMMA (S)	1.1111	1.1102	1.1093	1.1084	1.1078	1.1073	1.1073	1.1069	1.1065	1.1063	1.1060	1.1035
SON VEL, M/SEC	398.9	398.9	398.9	399.0	399.1	399.2	399.2	399.3	399.4	398.5	399.6	402.2
MOLE FRACTIONS												
CH_4	.00022	.00078	.00151	.00230	.00307	.00381	.00381	.00451	.00516	.00577	.00635	.01985
CO	.06187	.06151	.06101	.06047	.05992	.05938	.05938	.05887	.05838	.05792	.05748	.04515
CO_2	.28293	.28313	.28340	.28370	.28401	.28432	.28432	.28461	.28490	.28518	.28545	.29363
H_2	.12665	.12498	.12281	.12049	.11822	.11607	.11607	.11406	.11216	.11041	.10877	.07197
H_2O	.28942	.29043	.29173	.29312	.29447	.29576	.29576	.29696	.29807	.29911	.30007	.32094
KCL (S)	.07740	.07750	.07762	.07774	.07786	.07798	.07798	.07809	.07819	.07829	.07837	.08048
KCL	.00001	.00001	.00001	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
K_2CO 3(S)	.12029	.12043	.12060	.12079	.12098	.12116	.12116	.12133	.12149	.12163	.12177	.12504
NH_3	.00001	.00002	.00003	.00004	.00005	.00005	.00005	.00006	.00007	.00007	.00008	.00023
N^2	.04119	.04123	.04128	.04135	.04141	.044146	.04146	.04152	.04157	.04162	.04166	.042270

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN .50000E−05 FOR ALL ASSIGNED CONDITIONS

C(S)	C	CCL	CCL_2	CCL_3	CCL_4	CH	CH_2	CH_2O	CH_3
CH_3CL	CN	CNN	CN_2	COCL	$COCL_2$	C_2	C_2CL_2	C_2H	C_2H_2
C_2H_4	C_2H_6	C_2N	C_2N_2	C_2O	C_3	C_3O_2	C_4	C_4N_2	C_5
CL	CLCN	CLO	CLO_2	CL_2	CL_2O	H	HCL	HCN	HCO
HNCO	HNO	HNO_2	HNO_3	HO_2	H_2N_2	H_2O(S)	H_2O(L)	H_2O_2	K(S)
K(L)	K	KCN(S)	KCN(L)	KCN	KCL(L)	KH	KO	KOH	KOH(S)
KOH(S)	KOH(L)	KO_2(S)	K_2	K_2CO_3(L)	$K_2C_2N_2$	K_2CL_2	K_2O(S)	K_2O_2(S)	$K_2O_2H_2$
N	NCO	NH	NH_2	NO	NOCL	NO_2	NO_2CL	NO_3	N_2H_4
N_2O	N_2O_4	N_2O_5	N_3	O	OH	O_2	O_3		

NOTE. Weight fraction of fuel in total fuels and of oxidant in total oxidants.

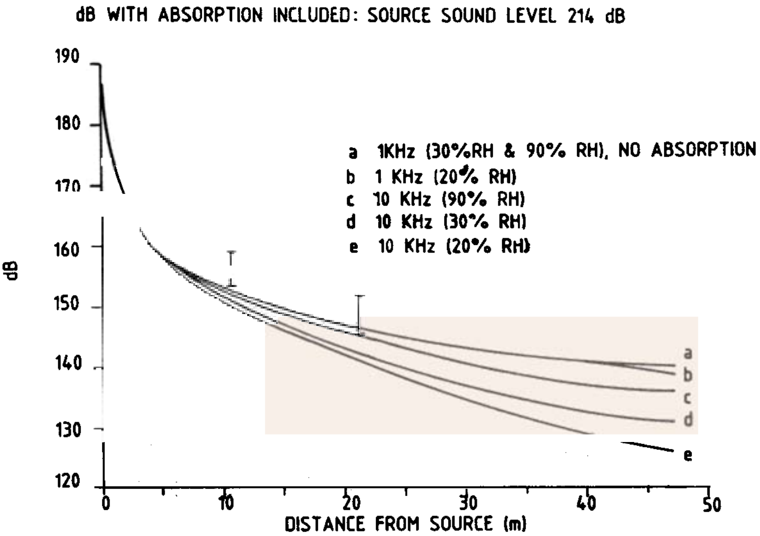


Figure 3. Predicted sound levels including absorption in moist ai

through iterations. The above relation assumes a plane wave and needs modifications for a spherically symmetric geometry. The results are shown in Fig. 3.

5. THE FLASH

There are obvious safety implications of a bright flash from a pyrotechnic. It is believed that both the flash intensity and duration are important. Space limitations prohibit a detailed discussion here. To produce a bright flash, the concept of the mechanical equivalent of light is useful. It is known that the ideal blackbody luminosity efficiency increases with the temperature and is also influenced by the spectral range. For the full spectrum, the efficiency is 20 lm/W at 2000° K and increases to 150 lm/W at 5000°K (approximately). These define the important upper bounds to what can be achieved for the flash luminosity.

6. SUMMARY

In this paper, some modeling and verification techniques were surveyed. It was shown that the subject, although very complex, may be amenable to formal analyses. The usual application of conservation equations and principles from the fields of optics and gas dynamics was shown to result in a simple analytical solution to the cloud (smoke) and noise problems. The most important observation is that the cloud size is essentially independent of the charge weight so long as the charge is small enough to be initiated completely at one spot upon ignition. As a practical matter, this appears to be in the 2-100 gm range. Experimental data were obtained, in a series of carefully conducted experiments, with charge weights ranging from 2 to 80 gm. This experimental verification implies that the pyrotechnics used for smoke/cloud generation need not to be heavy or expensive. The theoretical analysis also predicts that the material density of the product particles directly relate to the cloud size. This explains, the larger cloud sizes seen with the addition of zinc, for example, to the formulations.

The noise was seen to directly relate to the bursting pressure of the container (shell). A point of practical importance here is that the dynamic bursting pressure can be substantially higher than the static bursting pressure for many shell structures.

Aspects of the flash problem need further studies involving the physical nature of light emission from reactive media. Some general features with respect to personnel were referenced.

Larger charges needed to generate clouds in the hundreds of meters size range involve different considerations. The charge did not initiate simultaneously and some of the outer charge was dispersed before initiation. Experimental data were obtained with a maximum of 22 kg of charge. The cloud was obviously much larger than 5 m. The persistent problem of cloud dispersion in the atmosphere, due to local meteorological conditions, is seen as the major unsolved issue at the present time. Several ideas are being considered to solve this problem.

The use of pyrotechnics as inexpensive, ready, long-lasting gas generators was also discussed. Some thermochemical results were presented to show that a factor of three reduction in temperature is possible with simple additions to the formulation. Again, these are borne out by experimental measurements.

In summary, simple applications of concepts from combustion and gas dynamics can introduce great economy in pyrotechnic design.

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