

A New Model for Pyrotechnic Strobes

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Abstract: Existing models that purport to describe the mechanisms that occur in an ignited pyrotechnic strobe composition can all be shown to fail, in one respect or another, to match the observed behavior. By including separate reaction mechanisms for the smolder and flash phases, the proposed new model can avoid all such failings. An implementation of the model is then shown to be capable of reproducing the observed behavior of a specific strobe composition. The implementation's development provides insights into the relative significance of the physical and chemical processes that take place and of the relationship between the reactions that occur in the smolder and flash phases.

Keywords: Pyrotechnic strobe, Reaction mechanisms, Mathematical model

Introduction

Pyrotechnic strobes are compositions which burn in a cyclic manner, periodically alternating between quiescent (smolder) and more energetic (flash) phases. Although compositions of this type have been known for well over a century, they are still only poorly understood. Over the years, large numbers of such compositions have been discovered – for example, a recent review [1] lists over 100 – but most, if not all, were developed either by trial and error or by making modifications to a previously known formula.

One of the first attempts to understand the strobe mechanism was by Krone [2] who studied mixtures whose principal ingredients were barium or strontium nitrate and a 50:50 by weight alloy of aluminum and magnesium (magnalium). He noted that the inclusion of materials whose reaction products included significant amounts of gas greatly improved the sharpness of the flashes. In addition, his analysis of cooled residue from a composition that smoldered but failed to flash revealed the presence of aluminum, but almost no magnesium. This led him to propose that magnesium was preferentially consumed in the smolder phase, leaving aluminum to take part in the flash reaction. However, later

studies [3–5] have shown that Krone's chemical analysis of cooled residue is unlikely to have represented the actual state of the reaction at elevated temperatures and that, at least for true alloys of the two metals, there is no evidence for either of them being preferentially consumed at any stage of their oxidation, either in the temperature-controlled environments used in thermal analysis studies or in freely reacting mixtures.

Contemporaneously with Krone, Wasmann [6, 7] studied strobe compositions containing strontium or barium perchlorate with mixtures of complex organic polymers. In his discussion of likely mechanisms, he pointed out that, in addition to the chemistry, physical processes such as changes of state and heat transfer may also play a significant role.

Shimizu [8] built on these findings and put forward a general hypothesis; that a strobe composition should consist of a mixture of two oxidizer-fuel pairs – one responsible for the smolder reaction and the other to produce the flash. He devised several compositions of each type and showed that some, but not all, could be combined to create effective strobe compositions. It may be concluded that although Shimizu's hypothesis may well be a necessary condition, it cannot be a sufficient one.

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Jennings-White [9] examined a range of known strobe compositions and claimed that they could all be shown to contain the components required by both the smolder and flash reactions. Although many of the proposed reactions appear to make sense, the author freely admitted that, in some cases, the identification involved “*clutching at straws*”. No proof of the correctness of any of the proposed reactions was offered and, in fact, a later study [10] has shown that there is at least one case where the principal smolder reaction is not the seemingly obvious one that Jennings-White proposed.

Note that none of these considerations should be considered to be indications that Shimizu’s hypothesis may be false; the real problem appears to be the extreme difficulty of predicting the nature of the mechanisms that are likely to occur in freely reacting mixtures that contain several highly reactive components.

These difficulties are exemplified in the case of blue stobes. The first examples of compositions of this type – containing mixtures of ammonium perchlorate (AP), tetramethylammonium nitrate (TMAN) and copper powder – were reported by Jennings-White [11]. Further examples were reported by McCaskie [12], who used guanidinium nitrate (GN) instead of TMAN, with the aim of reducing the cost. Juknelevicius et al. [13] studied a range of TMAN-based compositions, using a variety of techniques that included video photography, spectroscopy and differential scanning calorimetry. A further study by some of the same authors [14] used similar techniques to investigate the behavior of blue strobe compositions based on aminoguanidinium nitrate (AGN). While both studies provided useful information regarding the nature of some of the mechanisms, the general state of understanding can perhaps best be summed up by the following quotation from the Conclusions section of that second paper, “*The smolder reaction seems to be caused by the decomposition of AGN with a copper catalyst and the flash reaction is possibly a combination of an exothermic reaction at the surface and ignition of flammable gases above. However, the origin of the cycling burning is unclear.*”

Although the experimental determination of the relevant reaction mechanisms is difficult, the creation of theoretical models of a strobe’s behavior has proved to be even more problematic; all three of the existing model proposals can be shown to fail to reproduce one or more of the observed aspects of strobe compositions. Many of these failures are discussed by Verbovytskyy and Harrison [1] so only a brief description of each model will be given here.

The studies by Feng et al. [15–17] and by Davies [18] are both based on existing theories of non-linear chemical kinetics and describe an oscillation resulting from the competition for oxygen between solid, liquid and gaseous magnesium. A problem shared by these two models is that they both predict that a given portion of the composition should sustain multiple cycles of oscillation, which is in contradiction with the observation that, in a functioning strobe, each combusting layer contributes to only a single cycle.

Corbel [19] made the valid point that the strobe mechanism shows a much greater similarity to the cyclically irregular combustion that can occur in self-propagating high-temperature synthesis (SHS) than it does to any other theory of oscillatory chemical reactions. In consequence, her model describes the layer by layer combustion of a cylindrical sample, where the temperature of any given layer is determined by two processes; the release of heat from the oxidation of magnesium in that layer and the conduction of heat to and from adjacent layers. She argued that the oscillatory behavior was the result of a delicate balance between these two mechanisms. However, it can be shown that this model does not exhibit an oscillatory behavior, but simply describes the variation in temperature of each layer as a smooth combustion wave travels at a constant rate through the sample.

In addition to these failings, none of the existing models predict one of the more evident features of the strobe mechanism – that each cycle consumes a definite thickness of the composition. All these issues indicate that a new or updated model is required if there is to be any chance of ever reconciling theory with experiment. The object of the current study is to develop such a model, and

to show that it is capable of replicating the behavior of a practical pyrotechnic strobe composition.

Experimental

The composition used in this study is listed in Table 1 and is one that belongs in a group of compositions that have previously been studied by Corbel [19] and Harrison [21,22]. All are bound with an additional 3 % (dry weight) of nitrocellulose dissolved in acetone.

Table 1. The composition

Constituent	%
Ammonium perchlorate	57.7
Magnalium	21.0
Barium sulfate	16.3
Potassium dichromate	5.0

The materials were obtained from a variety of sources and, although they appear to be reasonably pure, their precise degree of purity is not known. As a means of keeping the strobe frequency reasonably low, a relatively coarse grade of magnalium was used – passing 60 mesh and retained on 100 mesh screens, with particle sizes in the range from 150 to 250 microns.

The samples were made by lightly pressing the composition, while still moist, into thin-walled paper casings of internal diameter 6.35 mm and 2 cm in length. Each weighed casing was partially filled and left to dry. A Type G thermocouple was then introduced, resting on the surface of the composition before additional composition was pressed into the tube, to a total length of approximately 1 cm, and again left to dry. The dried sample's weight and the length of the column of composition were measured at each stage so that the total length and mass of the sample and the position and mass of the thermocouple were all known.

Each thermocouple was constructed as a five-turn twisted pair of 0.1 mm diameter tungsten and tungsten-rhenium alloy (26 wt% Re) wires that were obtained from Goodfellow Cambridge Limited. Copper leads were used to connect it to a DC amplifier of known fixed gain. The amplifier's output was connected to one of the analogue inputs of an Arduino Uno, which performed the A/D conversion and transmitted the data via a Bluetooth link to a Raspberry Pi that ran the controlling

software and wrote the data to file, for later analysis. Readings were taken at 1 ms intervals, and the recording software performed the voltage to temperature conversion with the aid of published tabular data [20].

The samples were ignited with a hand-held blowtorch and all trials were also recorded using a Panasonic HC-X900 video recorder operating at 50 frames per second.

The equations given in Section 2 indicate that knowledge of three physical properties is required. The density was calculated from the known mass and dimensions of the sample and the heat capacity was calculated as a weighted average of the published values for each of the component materials. The thermal conductivity was measured by a hot wire technique, as described by Alvarado et al. [23] (with careful control to ensure that the temperature was kept well below the composition's ignition point). Their values are listed in Table 2.

Table 2. Physical properties of the composition

Property	Value
Density, ρ (g/cc)	1.47
Heat capacity, c_p (J/g/K)	0.952
Thermal conductivity, k (W/cm/K)	0.0015

Figure 1 shows an example of the observed variation of temperature with time for an ignited sample, as the flame front approaches and passes the thermocouple's position. The flash frequency was 0.45 Hz, with each flash consuming approximately 1.5 mm of composition.

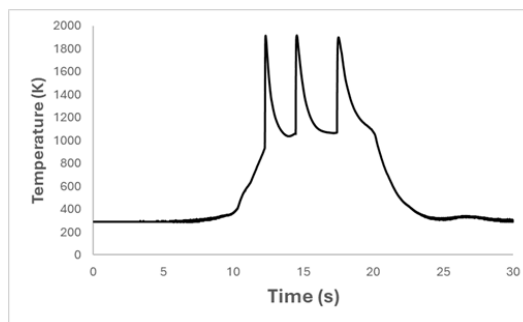


Figure 1. Example temperature profile

The Model

Of the models that have previously been proposed, the approach taken by Corbel – with its basis in the SHS mechanism and its inclusion of conductive heat transfers – appears to be

the most promising starting point, despite its failure to represent a cyclic process. Therefore, as in that model, we start by considering the layer-by-layer combustion of a composition. Unlike in any of the previously existing models, it was decided at the outset not to introduce dimensionless variables into the analysis. Although this results in some of the expressions becoming a little more cumbersome, it should simplify any later attempt to match the model to experimental data.

Let the sample be of density ρ and have a specific heat capacity c_p . Also let it be of length L ($= 10$ mm), divided into layers of thickness d ($= 0.05$ mm), and let the temperature of the i th segment be T_i . Equation 1 shows the general expression for the rate of progress of a reaction that takes place in that segment:

$$\frac{d\alpha_i}{dt} = A \cdot f(\alpha_i) \cdot \exp(-E_a/RT_i)$$

Equation 1.

where A is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, α_i represents (with a number lying between 0 and 1) how far the reaction has progressed and $f(\alpha_i)$ is the reaction model, i.e. how the kinetics of the reaction vary with α_i . If the reaction is exothermic, it will cause the temperature to rise at the rate shown in equation 2:

$$\frac{dT_i}{dt_{react}} = \frac{Q}{c_p} \cdot \frac{d\alpha_i}{dt}$$

Equation 2.

where Q is the amount of heat supplied to the material in that segment from the reaction occurring within unit mass of the composition.

The rate of change of temperature resulting from the conduction of heat to and from the two neighboring segments is:

$$\frac{dT_i}{dt_{cond}} = \frac{k}{\rho \cdot c_p \cdot d^2} \cdot (T_{i-1} + T_{i+1} - 2T_i)$$

Equation 3.

where k is the material's thermal conductivity.

The expression for the change in the reaction progress, $\Delta\alpha_i$, and the temperature, ΔT_i , in the n th segment during a short time interval Δt are then:

$$\Delta\alpha_i \approx \frac{d\alpha_i}{dt} \cdot \Delta t$$

Equation 4.

and:

$$\Delta T_i \approx \left(\frac{dT_i}{dt_{react}} + \frac{dT_i}{dt_{cond}} \right) \cdot \Delta t$$

Equation 5.

Up to this point, apart from the changes in notation, the overall reasoning closely matches that used by Corbel in the development of her model, but it is now necessary to consider why that model fails and what changes will be required to make the model perform correctly. An obvious approach is to see how well the model satisfies the general requirements that arose from the early studies by Krone, Wasmann and Shimizu.

As has previously been mentioned, the model already includes one of the physical processes – heat conduction – that Wasmann said are likely to play a significant role. It would be relatively straightforward to include other physical processes, such as changes of state or other means of heat transfer, should that prove necessary.

A more serious issue is that, with only one exothermic reaction, Corbel's model cannot satisfy the Shimizu hypothesis. Fortunately, a straightforward solution to this problem is to include a second reaction, again represented by equation 1 but with different parameter values, including a significantly higher activation energy than that of the first.

Equations 4 and 5 are used to determine the progress of each of the two reactions and the corresponding change in temperature in each segment of the sample during successive short time intervals. As in Corbel's model, the first and last segments are treated differently in terms of the transfer of heat. The first segment is considered to exchange heat only with the second segment, and the last segment is treated as though it is bounded by a region that remains at an ambient temperature of 293 K (a condition which is slightly different from the one that Corbel placed on that segment, but

results in a similar behavior). In addition, the ignition of the sample is simulated by holding the first segment at a temperature T_{ign} for a time τ_{ign} .

These calculations are all that is needed to model the smolder phase, but additional actions are required during the flash phase. In Corbel's model, a segment is deemed to be taking part in the flash reaction if its temperature exceeds the boiling point of the metal fuel. Each such segment is simply discarded, with no further action considered to be necessary. However, observation of the behavior of a typical strobe composition suggests that a more complex treatment is required, taking into account both that the flash reaction in one segment will transfer heat into neighboring segments and that the energetic nature of the reaction results in the dispersion of nearby segments, including ones that, according to Corbel's criterion, are not themselves undergoing the flash reaction. At the end of a flash phase the newly exposed surface must have a temperature that is lower than that needed to initiate the flash, but still sufficiently high to maintain the smolder reaction.

As in Corbel's model, the transition from the smolder to the flash phase is deemed to occur when the temperature of a segment exceeds some given value, T_f . However, unlike in her model, such segments are not immediately removed from the calculation. Instead, the leading segment is removed on each subsequent iteration through the sample, until the new leading segment's temperature falls below some other given value, T_{sm} , at which point the flash phase is deemed to terminate. This technique was chosen to ensure that the flash phase exists for a finite length of time, and that there is an opportunity for some of the energy of the flash reaction to be transferred to neighboring segments, thereby reproducing at least some of the complexity of the observed behavior. Although the discarded segments play no further part in the interaction, at each iteration their temperature is set equal to that of the current leading active segment, thereby replicating – at least in part – the response of the thermocouple once the flame front has passed by.

With a suitable choice of the parameters, the model can be shown to represent the characteristic cyclic behavior of a pyrotechnic strobe composition, with each portion of the material taking part in only one cycle. However, while this result indicates that the model has promise, it remains to be shown that it continues to predict a strobing action when the parameters are matched to the processes that are found to occur in a real, practical example of a strobe composition.

Results and Discussion

It is worth pointing out that, while the profiles such as that shown in Figure 1 show significant differences of detail from sample to sample – possibly because of differing alignments between the thermocouple and the closest section involved in a reaction cycle – the overall picture remains broadly the same. Note also that it is only the portion of the curve up to the first flash peak that is relevant to the subsequent analysis; beyond that point the flame front has passed the thermocouple's position, and the measured temperature is that of the largely gaseous reaction products as they flow past the thermocouple. Given the large difference in the rate of heating between the smolder and flash phases, it proved necessary to analyze the two stages separately.

For any given set of parameters – including the choice of the reaction model, $f(\alpha)$ – equation 1 defines how the reaction rate varies with temperature and, for an exothermic reaction, via equation 2 the variation of the rate of heating with temperature. Conversely, for a known relationship between the rate of heating and the temperature, it should be possible, at least in principle, to find values for the reaction parameters. It was therefore decided that this should be the approach to use in the attempt to match the reaction parameters to the observed behavior.

Unfortunately, the use of this method raises some practical difficulties. Firstly, and perhaps most seriously, the intrinsic noisiness of the temperature profiles is greatly emphasized when the time derivative is taken. The effect of this issue was reduced by applying a smoothing filter to each of the individual profiles before taking the derivative. The smoothing algorithm is one described by Savitzky and Golay [24] and

later used by Boddington et al. [25] and is based on a least mean squares fit of 25 consecutive data points to a second-order polynomial. The experimental midpoint was replaced by the calculated value and the treatment advanced by one point. The procedure was repeated until the root mean square of the difference between successive smoothings was less than the mean experimental uncertainty of ± 5 K in the temperature measurements. Secondly, the sample-to-sample differences noted above result in significant differences in the shape of the relationship, but the effect of this issue was reduced by taking the average of five separate recordings. The resulting relationship for the processes that occur in the smolder phase is shown in Figure 2.

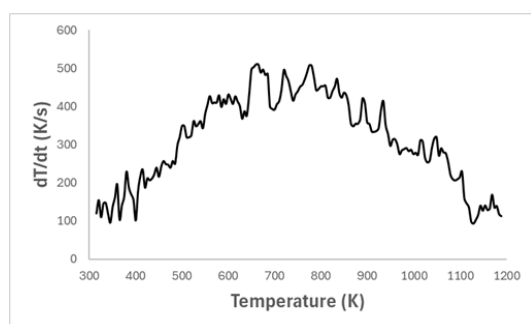


Figure 2. An average of five smoothed records of the observed variation of the heating rate with temperature during the smolder phase

Before proceeding further with the analysis, it is first necessary to determine what reactions need to be included. For the type of composition considered in this study, both Jennings-White [9] and Corbel [19] have proposed that the reaction responsible for the smolder phase is the oxidation of either or both metal fuels in the oxygen-rich gases released by the decomposition of AP. This decomposition is exothermic and is therefore likely to contribute to the increase in temperature during this phase – a fact that was ignored by Jennings-White, and only referred to in passing by Corbel, as a factor that promotes the oxidation of the metal fuel. However, a more recent study [22] indicated that AP decomposition is the principal source of heat in this phase, and that there is only a relatively minor contribution that results from the oxidation of a small proportion of the metal fuel.

However, as has been pointed out by Vyazovkin and Wight [26], the thermal

decomposition of AP is a highly complex process, involving a variety of overlapping chemical and physical phenomena. Those authors present the results from numerous studies, reporting activation energies that range from 37 to 260 kJ/mol, together with a wide variety of possible functional forms for the reaction model, $f(\alpha)$, and conclude that an accurate description must allow for the activation energy to vary significantly as the reaction progresses. In the current study the situation is further complicated, both by any catalytic action of potassium dichromate and by the possibility that the freely reacting material may not follow the same reaction paths that are observed in laboratory studies, where the rise in temperature is relatively slow and externally controlled.

Similar issues exist in the attempt to represent the kinetics of the oxidation of the metal fuel. Again, there is no obvious choice for the reaction model and, as reported by Nie et al. [4], the activation energy varies during the reaction's progression from below 50 to over 200 kJ/mol. The possibility that the rate of this reaction is also likely to depend on the local concentration of oxygen-rich gas resulting from the AP decomposition – another unknown factor – appears to add yet further complication.

In view of all these issues it was decided that it would be impractical to attempt to create a model that accurately represents such a complex set of physical and chemical processes. Instead, a simple model was chosen, where each reaction is represented by the relation of equation 1 with constant parameters.

The reactions are arbitrarily assumed to follow an n th order reaction model, with the further restrictive assumption that n has an integer value. Note that this choice, whose functional form is shown below, was made purely on the grounds that it is one of the simplest of the range of functional forms that have been proposed.

$$f(\alpha) = (1 - \alpha)^n$$

Equation 6.

The physical properties listed in Table 2 were also assumed not to vary with either temperature or changes in composition as the

reactions progressed, and the values of Q for each reaction were initially chosen to approximately match the estimated overall changes in temperature for each reaction.

Several studies [3–5] conclude that, in the oxidation of an alloy of the two metals, both aluminum and magnesium are consumed at all stages of the reaction. From that conclusion, together with the observation that only a small proportion of the metal is consumed in the smolder phase, it was decided to make the further simplifying assumption that this oxidation can be approximated by a single reaction mechanism, rather than attempting to treat the two metals separately.

The parameters were then adjusted until a reasonable fit with the observed smolder phase behavior was obtained. Early in this process it was found that the observed increase in the rate of heating at temperatures below 600 K could only be reproduced if the thermal conductivity was set to 0.0029 W/cm/K – almost twice the observed value that is listed in Table 2. This appears to indicate that other means of heat transfer – for example, radiation or the diffusion of gaseous reaction products – are likely to be involved.

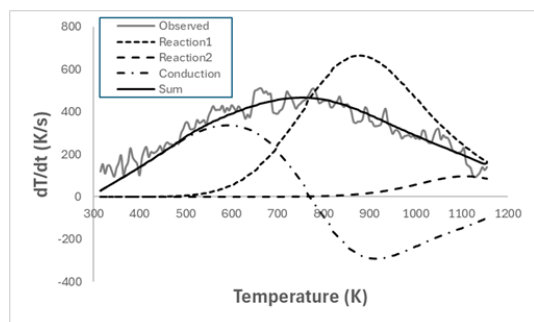


Figure 3. The match between observation and the model's output for the processes that occur in the smolder phase

The match with observation for the processes that occur in the smolder phase is shown in Figure 3. It is interesting to note that, despite the uncertainties regarding the precise mechanism, heat transfer plays as significant a role as does the chemistry.

A similar treatment was applied to the flash phase. In this case there appear to be no existing studies of the reaction between magnesium and barium sulfate, so there was no initial guidance for the possible values of the kinetic parameters. In addition, the reaction is far more energetic than those that

occur during the smolder phase, resulting in much of the material being dispersed while the reaction is taking place. In consequence, the parameters that provide a good fit to the observed behavior during this phase are unlikely to be truly representative of the actual chemical processes that occur in this phase.

Table 3. The reaction parameters

Parameter	Reaction 1 (Smolder)	Reaction 2 (Smolder)	Reaction 3 (Flash)
A (/s)	4.17e+03	4.82e+04	2.00e+06
n	4	2	3
E_a (kJ/mol)	55.6	96.6	160
Q (J/g)	940	150	1500

The best fit reaction parameters for both phases are listed in Table 3. However, it should be borne in mind that the values of A , n , and E_a were determined by a process of trial and error, so they should all be viewed with a degree of caution; there may be other sets of values that could result in a similarly good fit. Furthermore, their values would almost certainly be different if an alternative functional form had been chosen for the reaction model.

It is also worth noting that, because of losses of heat to the environment, all three Q values are lower than would be expected from a consideration of the changes of enthalpy that are associated with each reaction. This is especially true for reaction 2; in this case the exceptionally low value is an expression of the fact that – as indicated by a previous study [22] – by the conclusion of the smolder phase only a relatively small fraction of the available metal fuel has been consumed.

Table 4. Values of some additional parameters

Property	Value
Ignition temperature, T_{ign} (K)	1100
Ignition time, τ_{ign} (s)	1.5
Flash temperature, T_{fl} (K)	2000
Smolder temperature, T_{sm} (K)	1125

Table 4 lists the values given to four additional parameters that were defined in Section 2 and are worthy of further discussion. The model's behavior is largely insensitive to the values given to T_{ign} and τ_{ign} , whose principal effects are to determine the delay that precedes the appearance of the first flash. It is also relatively insensitive to the choice of T_{fl} , provided its value lies within the range where the temperature rises rapidly at the start of the flash reaction.

In contrast, the behavior is strongly dependent on the value chosen for T_{smi} : a higher value increases the strobe frequency, and a lower value decreases it. If the value is sufficiently low, the reaction terminates after the first flash. On the other hand, if the value is sufficiently high the flashes effectively fuse into a single reacting phase that consumes most of the material. The choice of the value for this temperature also affects the number of segments that are consumed in each cycle – the lower the value the greater the number. The effect is as if the flash reaction were becoming more energetic, dispersing an increasing amount of material.

In a strobe composition, this correspondence can be viewed in reverse; a more energetic flash reaction will disperse a greater amount of material, resulting in the surface of the remaining composition being lower in temperature. If the reaction is sufficiently energetic, the temperature of the remaining material will be too low to maintain the smolder reaction and the composition will self-extinguish. On the other hand, if the reaction is too weakly energetic, the temperature at the surface will be sufficiently high to maintain the flash reaction and burning will be continuous. It follows that, for any given smolder composition, there must be a limited range of flash reactions that can maintain a strobing action. Not all possible combinations of smolder and flash compositions will work – a conclusion that Shimizu [8] reached from an experimental point of view.

Although the model accurately reproduces most of the composition's behavior, the flash reaction's exponential dependence on temperature results in the transition from smolder to flash being far more gradual than the abrupt change that is observed. It is not clear what processes are responsible for the sudden change, although a previous study [22] has shown that the flash reaction does not become significant until the local concentration of AP is almost exhausted, which could imply that the reaction is in some way inhibited by its presence. Alternatively, the sudden change might be a consequence of the observation, first made by Shimizu [8], that the flash phase is generally preceded by the formation of one or more hot spots that rapidly grow and fuse to cover the entire surface, which may result in a more sudden rise in

temperature in the surrounding material than would otherwise be expected. However, regardless of whether either of these two mechanisms is or is not the cause, there does not, at present, appear to be any means to realistically model the effect. It was therefore decided to reproduce this feature by simply inhibiting the flash reaction at temperatures below a value of 1200 K.

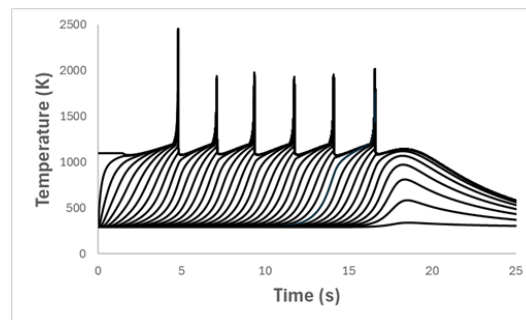


Figure 4. Sample model output, showing the calculated temperature profiles at points 0.25 mm apart, along the full 10 mm length of the composition

The resulting output of the model is shown in Figure 4. The mean frequency is 0.42 Hz and each cycle consumes 1.4 mm of material; both of these are close to the observed values for the composition that is being modeled.

Conclusions

Following a brief review of existing studies of pyrotechnic strobe compositions, it is pointed out that none of the previously proposed models can correctly reproduce all the observed features of their behavior. A new model is presented which, while broadly following Cobel's SHS-based approach, ensures a cyclic behavior by introducing separate reactions for the smolder and flash phases.

An implementation of the model, replicating the behavior of a previously studied AP-based strobe composition, is presented. This implementation is based on several approximations and simplifying assumptions whose principal justification is that they enable a close fit between the model's output and the observed properties. It is quite possible that future advances in the understanding of the processes involved will enable a more realistic implementation to be developed.

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References

- 1 Y. Verbovytskyy, R. Harrison, Pyrotechnic Strobe Compositions: an Overview, *Propellants, Explosives, Pyrotechnics*, Vol. 47, 2022, e202100311.
- 2 U. Krone, Strahlungsemission in Intervallen Oscillierende Verbrennung pyrotechnischer Sätze, in: *Pyrotechnik: Grundlagen, Technologie und Anwendung, Jahrestagung 1975*, Karlsruhe, Germany, June 11–13, 1975, pp. 225–237.
- 3 Y. Aly, E. L. Dreizin, Ignition and combustion of Al-Mg alloy powders prepared by different techniques, *Combustion and Flame*, Vol. 162, 2015, pp. 1440–1447.
- 4 H. Nie, M. Schoenitz, E. L. Dreizin, Oxidation of differently prepared Al-Mg alloy powders in oxygen, *Journal of Alloys and Compounds*, 685, 2016, pp. 402–410.
- 5 R. Harrison, A Thermal Study of Mixtures of Micron-sized Copper (II) Oxide, Aluminum and Magnalium, *Journal of Pyrotechnics*, 2020, pp. 1–10.
- 6 F.-W. Wasmann, Pulsierend abbrennende pyrotechnische Systeme, in: *Pyrotechnik: Grundlagen, Technologie und Anwendung, Jahrestagung*, Karlsruhe, Germany, June 11–13, 1975, pp. 239–250.
- 7 F.-W. Wasmann, The Phenomenon of Pulsating Burning in Pyrotechnics, *Proceedings of the fifth international pyrotechnic seminar*, July 12–16, 1976, Denver Research Institute, University of Denver, Denver, Colorado, USA, pp. 643–651.
- 8 T. Shimizu, Studies on Strobe Light Pyrotechnic Compositions, *Pyrotechnica*, Vol. 8, 1982, pp. 5–34.
- 9 C. Jennings-White, Strobe Chemistry, in: *Pyrotechnic Chemistry*, Journal of Pyrotechnics Inc., Whitewater CO, 2004, Ch. 15.
- 10 R. Harrison, A Study of a Set of Nitrate-Based Pyrotechnic Strobe Compositions, *Journal of Pyrotechnics*. 2023, pp. 1–7.
- 11 C. Jennings-White, Blue Strobe Light Pyrotechnic Compositions, *Pyrotechnica*, Vol. 14, 1992, 33–45.
- 12 E. McCaskie, A new Method for the Production of Blue Strobe Stars, *Pyrotechnica*, Vol. 15, 1993, pp. 35–45.
- 13 D. Juknelevicius, A. Dufter, M. Rusan, T. M. Klapötke, A. Ramanavicius, Study of Pyrotechnic Blue Strobe Compositions Based on Ammonium Perchlorate and Tetramethylammonium Nitrate, *European Journal of Inorganic Chemistry*, Vol. 7, 2017, pp. 1113–1119.
- 14 D. Juknelevicius, T. M. Klapötke, A. Ramanavicius, Blue Strobe Pyrotechnic Composition Based on Aminoguanidinium Nitrate, *Propellants, Explosives, Pyrotechnics*, Vol. 44, 2019, pp. 1466–1471.
- 15 C. Feng, Q. Zeng, L. Wang, X. Fang, Study of the Mechanism of Oscillatory Solid-phase Combustion by a Non-linear Chemical Kinetic Model, *Journal of the Chemistry Society Faraday Transactions*, Vol. 92(16), 1996, pp. 2971–2975.
- 16 C. Feng, Z. Lio, Q. Zeng, Y. Xu, S. Xu, The Nonlinear Chemical Reaction Kinetics of $\text{NH}_4\text{ClO}_4 + \text{Mg} + \text{K}_2\text{Cr}_2\text{O}_7$ System 1. Experimental Phenomenon of Solid - Phase Oscillatory Combustion, *Acta Chimica Sinica*, Vol. 57, 1999, pp. 229–235.
- 17 C. Feng, Z. Liu, Q. Zeng, S. Xu, The nonlinear chemical reaction kinetics of $\text{NH}_4\text{ClO}_4 + \text{Mg} + \text{K}_2\text{Cr}_2\text{O}_7$. 2: Chemical models of the solid phase oscillatory combustion, *Acta Chimica Sinica*, Vol. 57, 1999, pp. 339–344.
- 18 M. L. Davies, A Thermokinetic Model for the Combustion of Strobe Composition, *Journal of Pyrotechnics*, Vol. 27, 2008, pp. 42–49.
- 19 J. M. L. Corbel, *New insights into strobe reactions: An intriguing oscillatory combustion phenomenon*, Ph. D. Thesis, 2013, Universiteit Utrecht, Netherlands.
- 20 F. R. Caldwell, Thermocouple Materials, *NBS Monograph (U.S.) No. 40*, 1962, p.34.
- 21 R. Harrison, Some Factors Affecting the Performance of a Class of Ammonium Perchlorate-Based Pyrotechnic Strobe Compositions, *Journal of Pyrotechnics*, 2021, pp. 1–10.
- 22 R. Harrison, A Study of a Set of Pyrotechnic Strobe Compositions Based

- on Ammonium Perchlorate, *Journal of Pyrotechnics*, 2024, pp. 21–27.
- 23 S. Alvarado, E. Marin, A. G. Juárez, A. Calderón, R. Ivanov, A hot-wire method based thermal conductivity measurement apparatus for teaching purposes, *European Journal of Physics*, Vol. 33, 2012, pp. 897-906.
- 24 A. Savitzky, M. J. E. Golay, Smoothing and Differentiation of Data by Simplified Least Squares Procedures, *Analytical Chemistry*, Vol. 36, 1964, pp. 1627-1639.
- 25 T. Boddington, P. G. Laye, J. R. G. Pude, J. Tipping, Temperature Profile Analysis of Pyrotechnic Systems, *Combustion and Flame*, Vol. 47, 1982, pp. 235-254.
- 26 S. Vyazovkin, C. A. Wight, Kinetics of Thermal Decomposition of Cubic Ammonium Perchlorate, *Chemistry of Materials*, Vol. 11, 1999, pp. 3386-3393.