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Yellow-Flare Performance Improvement of PVC Addition into Mg-Sodium Nitrate-Based Pyrotechics

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Abstract—Light pyrotechnics is one strategic defence equipment for civil and military purposes. Additives act as one of the factors that affect the flame in pyrotechnics. Additives were used to slow down the combustion rate so that the flare could burn for a long time without drastically reducing the flame performance of the flare. This study focused on the performance of pyrotechnic flames with variations of PVC as a density-increasing material because it was in the form of a polymer and had high-chlorine content, resulting in a mixture that is difficult to burn. The experiment results exhibited that pyrotechnics without PVC showed intensity with an emission spectrum of 577-585 nm, light intensity of 723-1184 lux, and burning rate of 3.22-3.31 g/s. Increasing the PVC additive composition to 1.5 gr showed emissions with a wavelength of 596-597 nm, decreased intensity from 91-183 lux, and a slower burning rate of 0.72-0.88 g/s. The use of PVC was effectively applied in the 1.76-10.21% fraction and was actively able to slow down the rate of combustion of pyrotechnic mixtures. Hence, PVC could slow down the burning rate and increase density. Adding PVC in yellow pyrotechnics would slow down the burning rate of the pyrotechnic sample with the side effect of reducing the brightness of the yellow color and the intensity of the light.

Keywords—*Additives; Burn rate; Emission spectrum, Luminosity; Pyrotechnics*

1. INTRODUCTION

Pyrotechnics are one of the defence equipment components in the form of high-energy materials with a lower explosion speed than explosives and produce specific effects, such as those found in light pyrotechnics. Pyrotechnic materials are commonly used by civilians, such as in theatre arts, pyrotechnics, and road flares. These materials have broad uses in the military, such as signal lighting, smoke grenades for obscuration, propellant for delay compositions, flares, primer formulations, and incendiary devices [8]. In addition, in many cases, pyrotechnic materials are widely used to signal help by soldiers trapped in danger or as a post sign on the battlefield.

Light pyrotechnics are high-energy materials with a lower burning rate than explosives and produce a combination of light, color, smoke, heat, and sound for diverse civil and military applications [1]. Pyrotechnic light is a material that burns into a flame in the gas phase and produces unique characteristics that emit narrow lines or bands of light in the visible region (380-780 nm) of the electromagnetic spectrum [2]. Pyrotechnic light appears in several colors across the spectrum, ranging from yellow [3], red [4], green [5], purple [6], to blue [7]. **Table 1** shows the wavelengths of colors produced by the emission of pyrotechnic materials.

The materials used are generally in the form of oxidizers, fuels, and other additives, such as metals and binders to improve the performance of each pyrotechnic material. Oxidizers function as electron

Table 1. Pyrotechnic material emission spectrum [2]

Wavelength (nm)	Emission Color
380-435	Violet
435-480	Blue
480-490	Blue-green
490-500	bluish green
500-560	Green
560-580	Yellowish green
580-595	Yellow
595-650	Orange
650-780	Red

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acceptors and lose oxygen (undergoes reduction). The oxidizer must be rich in oxygen so that at high temperatures it produces oxygen gas into the environment [2]. The fuel becomes an electron donor when it reacts with an oxidizer to undergo oxidation. The fuel functions as an oxygen recipient from the oxidizer to produce heat energy with certain effects, such as color, light, smoke, and noise [2]. In addition, some essential additives in pyrotechnic mixtures can increase the density, modify the burning rate of the mixture, and provide a loading process in the pyrotechnic container [9].

Light pyrotechnics also have various formulas based on their respective functions, including yellow pyrotechnics with a base material of $NaNO_3$ as an oxidizer, fuels with various compositions in the form of Magnesium (Mg), and additives in the form of PVC or Shellac-Gum according to their respective uses [3].

Different compositions also impact their performance, including the emitted color spectrum, luminosity [3], and the burning rate when ignited [10]. Color spectrum can be detected using spectrometry methods, which allows chemists to study the characteristics and structure of matter and molecules [11]. An emission spectrometer is a chemical analysis instrument that detects polychromatic light from the electron excitation of reacting pyrotechnic materials. Pyrotechnic materials that undergo reactions emit and excite electrons released from their molecules. This electron excitation is recorded in a spectrum form, expressed as wavelength according to the type of electrons in the molecule to be analyzed.

Luminosity is a parameter that determines the performance of light pyrotechnic materials. Luminosity is used to measure the brightness of the room or the results of burning the pyrotechnic materials. The burn rate is the speed or rate of burning of the pyrotechnic materials. The burn rate measures the rate at which a pyrotechnic material burns when exposed to heat or flame [2]. The burning rate is an essential parameter in the design and development of pyrotechnic equipment, such as pyrotechnics, firecrackers, or other pyrotechnic devices [1].

PVC itself is a non-energetic material that functions as an additive to flares, where its function is used to increase the density and as a potential additive at a relatively low cost. The thermoplastic nature with a fairly high LOI (Limiting Oxygen Index) makes PVC suitable for use to slow down the burning rate. PVC generates numerous chlorine radicals (more than 60%) at higher temperatures, causing significant changes in the pyrotechnic performance, especially making the burning rate slower [12]. **Fig. 1** explains that the shape of the PVC polymer causes radical decomposition, which later affects the pyrotechnic performance. The variation of PVC in the flare mixture used as an additive also needs to be known in terms of the amount of the mixture so that its effect does not reduce the luminosity and spectrum drastically of the flare used.

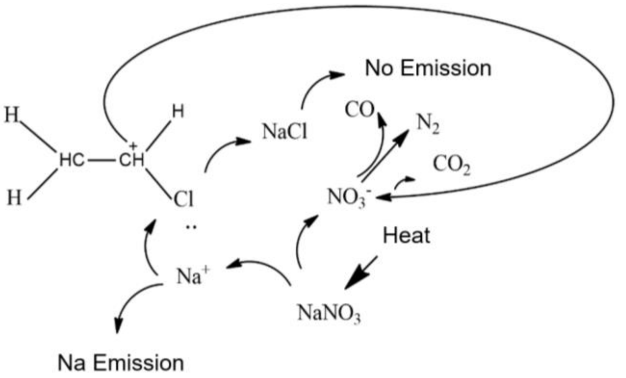

Fig. 1. Polyvinylchloride reactions when reacting with yellow flare materials [2],[3],[13],[14]

Current research focuses on flare durability, where flare researchers want to create flares that last a long time but still burn brightly. Thus, they do not interfere with the luminosity and brightness of the flare when lit. PVC, with its polymer form and the chlorine it contains, is expected to be able to slow down the burning rate of flares, although it will have a slight impact on the brightness and yellow flame color of the flare, although not as drastically as when PVC is not used. Thus, this research can determine the appropriate amount of PVC additive without causing a faint flare and can still be used optimally.

2. EXPERIMENTAL SECTION

2.1. Materials

The materials used were sodium nitrate ($NaNO_3$) (99%) from Loba Chemie, polyvinyl chloride (PVC) resin PSM-31 (97%) from Kaneka Corporation, Mg powder 200 mesh (95%) from Tangshan Weihao Magnesium Powder Co., Ltd, and black powder detonator.

2.2. Instrumentation

The tools used were emission spectrometer, luxmeter HS1010, stopwatch, camera, 12 V electric current source, laptop Lenovo Thinkbook 14, and Ruihua handpress toolkit.

2.3. Pyrotechnics Mixture Preparation

The research procedure involved mixing three basic components of pyrotechnic materials (Mg powder, $NaNO_3$, and PVC resin) with different compositions of materials. **Table 2** lists the compositions used in this experiment. A black powder detonator was installed into the pyrotechnics mixture to ignite the pyrotechnics with an electric current of 12 V.

2.4. Pyrotechnics Performances Determination

Pyrotechnic samples were ignited in performance measurement tools made from 4 parts including a gas chamber, burning rate tester, emission spectrometer, and luxmeter. The emission spectrometer measures the wavelength of the pyrotechnics samples. Luxmeter measures the luminosity of pyrotechnics. The burn rate tester measures the pyrotechnic burn time. The gas chamber releases the gas from pyrotechnics, and the gas does not interfere with the performance measurements. **Fig. 2** shows the instrument used in this experiment. Pyrotechnic samples are ignited with a 12 V electric current that causes combustion in pyrotechnics and generates yellow light.

Table 2. Pyrotechnic composition experiments

Amount of oxidizer (g)	Fuel quantity (g)	Additive mass (g)	Additive Percentage (%)
5.86	4.14	-	0
5.86	4.14	0.50	5
5.86	4.14	0.70	7
5.86	4.14	1.20	12
5.86	4.14	1.50	15

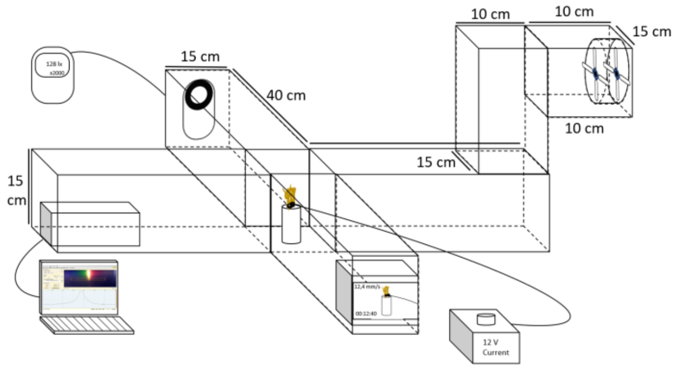

Fig. 2. Pyrotechnics measurement tools

3. RESULT AND DISCUSSION

3.1. Yellow Flame Wavelength Measurements

The first step in determining the effect of the PVC additives on the pyrotechnic performance is to determine the yellow color of the pyrotechnic sample. This aspect is measured using an emission spectrometer that contains a monochromator that decomposes light into monochrome forms. The dominant yellow color is indicated by a yellow wavelength of around 575-600 nm [3].

The observations focused on the emission spectrum to determine the dominant wavelength of the yellow pyrotechnic material with the PVC additive. **Fig. 3** and **Table 3** show that increasing the amount of PVC content also increases the wavelength. Furthermore, **Fig. 3** shows that increasing the wavelength results in a color change from yellow to orange. It can also be concluded that increasing the amount of PVC could decrease the intensity of the yellow color shown in **Fig. 3**, and then the orange color would be more dominant.

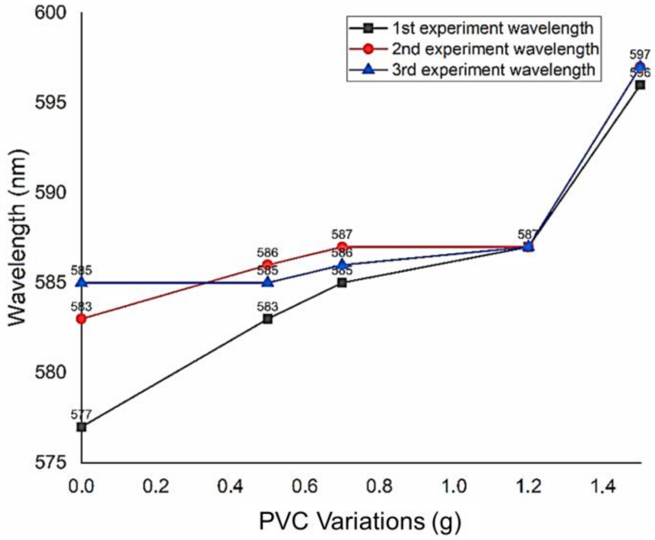

Fig. 3. Graph of PVC variations effect in emissions wavelength

Table 3. Pyrotechnic composition experiments

PVC Variation (g)	Wavelength (nm)				
	Experiment			Average	SD
0.00	577.00	583.00	585.00	581.67	5.66
0.50	583.00	586.00	585.00	584.67	
0.70	585.00	587.00	586.00	586.00	
1.20	587.00	587.00	587.00	587.00	
1.50	596.00	597.00	597.00	596.67	

3.2. Luminosity in Pyrotechnics Samples

The second aspect of performance testing is measuring the brightness or energy measured from pyrotechnic combustion. This component is pivotal considering the effective use of flares, which are mostly used at night [15]. The measurement of overall brightness and pyrotechnic energy levels can be identified using a luxmeter at a predetermined distance. This measurement produces units in the form of lux, which indicates the amount of polychromatic light emitted by the pyrotechnic sample.

Table 4 shows the highest luminosity achieved by the sample without PVC, with an average luminosity of 904.33 lux, followed by the additive of 0.50 g PVC with 573.00 lux, the additive of 0.70 g PVC with 395.67 lux, the additive of 1.20 g PVC with 229.33 lux, and the lowest value with the additive of 1.50 g PVC with a value of 123 lux.

The decrease in luminosity indicates that PVC is not a good additive because this material is included in low-energy fuels, where the reaction occured does not produce heat, thus reducing the luminosity of the light produced [16]. The use of PVC is also less effective because PVC is a polymer that produces many gas products [13]. Meanwhile, gas compound products do

Table 4. Luminosity from pyrotechnics sample

PVC Variation (g)	Highest Luminosity (lux)				
	Experiment			Average	SD
0.00	723.00	806.00	1184.00	904.33	3.08
0.50	464.00	419.00	836.00	573.00	
0.70	373.00	313.00	501.00	395.67	
1.20	105.00	283.00	300.00	229.33	
1.50	91.00	183.00	95.00	123.00	

not provide light and only absorb energy from the reaction, resulting in heat formation and preventing the formation of compounds that can produce emissions such as MgO [1] and sodium [3].

3.3. Pyrotechnics Burning Rate Performances

The third component crucial to pyrotechnic light performance measurements is the burning rate. The burning rate in pyrotechnics indicates how long the pyrotechnic flame can last for a certain period. The measurement is also quite simple, namely using a stopwatch or timer on the camera. However, formula, density, and amount of pyrotechnic materials are required to be adjusted to determine how each material affects the burning rate. **Fig. 4** shows a graph of the yellow pyrotechnic burning rate with PVC variations, and **Table 5** lists the pyrotechnic flame burning rate values.

Pyrotechnic variations without PVC additives have a burning rate ranging from 3.22 to 3.31 g/s, 0.50 g PVC pyrotechnics have a burning rate ranging from 1.31 to 1.53 g/s, 0.70 g PVC pyrotechnics with a range of 1.06 to 1.07 g/s, 1.20 g PVC pyrotechnics with a range of 0.93 to 1.02 g/s, and 1.50 g PVC pyrotechnics with a range of 0.72 to 0.88 g/s. **Table 5** shows the burning rate with a higher PVC composition produces a lower value. In contrast, the pyrotechnic mixture without PVC has the fastest burning rate compared to the mixture, with the addition of PVC additives. The bar chart in **Fig. 4** with the x-axis as the variation of PVC and the y-axis as the burning rate, shows that the addition of PVC impacts all three experiments in the lower bar chart, indicating that the burning time of the pyrotechnic sample will be longer.

Table 5. Burning rate of pyrotechnics sample performances

PVC Variation (g)	Burning Rate (g/s)				
	Experiment			Average	SD
0.00	3.24	3.31	3.22	3.26	1.01
0.50	1.53	1.31	1.47	1.44	
0.70	1.07	1.07	1.06	1.07	
1.20	0.93	0.94	1.02	0.96	
1.50	0.82	0.72	0.88	0.81	

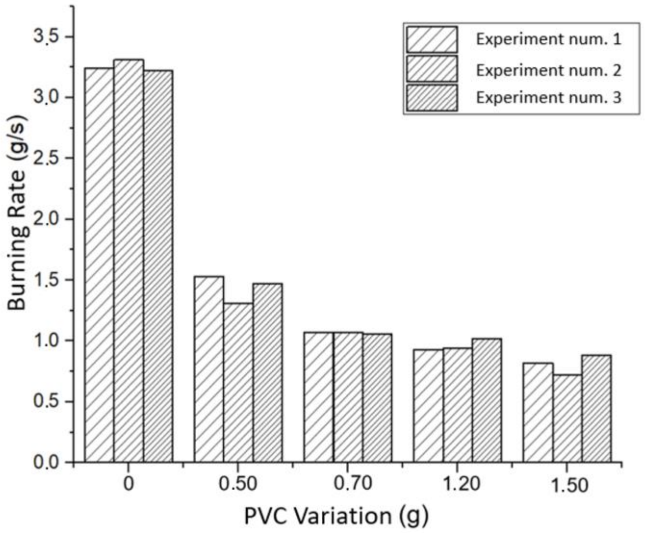

Fig. 4. Burning rate graph of pyrotechnics sample performances

3.4. Optimum Fraction in Pyrotechnics Performances

The optimum fraction for the pyrotechnic formulation was determined by determining the average value of each parameter in **Table 6**. Then, the average value of each parameter was used as an equation to determine the similarity and relationship between the x-value and y-value as a whole until the PVC fraction reached 15% [17]. This restriction is used because the higher value impacts on the ineffectiveness of pyrotechnic performance, starting from the flame, durability, and sensitivity of the material itself.

Table 6. Average value of pyrotechnics performance indicators

No.	PVC Additives (g)	Dominant Wavelength (nm)	Luminosity (lux)	Burn Rate (g/s)
1.	0.00	581.67	904.33	3.26
2.	0.50	584.67	573.00	1.44
3.	0.70	586.00	395.67	1.07
4.	1.20	587.00	229.33	0.96
5.	1.50	596.67	123.00	0.81

The optimum fraction of pyrotechnic samples was determined, and the average performance results of each of the most influential components were mapped (luminosity, emission spectrum, and combustion rate). Then, from the average, an exponential equation was calculated, which results were closest to the experimental results using Origin software. Based on the calculation results, the emission spectrum (black graph) produced the equation $y=0.05e^{(x/2,73)} + 583.53$, luminosity (red graph) produced the equation $y = 991.55\ e^{(-0,13x)}$, and the burning rate (blue graph) produced the equation $y = 2.55\ e^{(-x/0,36)} + 0.90$. The meeting point with the flare boundary in the literature was then calculated. Based on these results, the optimum boundary point was obtained with each pyrotechnic performance indicator at its best point.

Fig. 5 shows the graph of light, dominant wavelength, and burning rate for PVC masses up to 15% of the mixture. **Fig. 5** shows an illustration of the flame, burning rate, and intensity expected to obtain pyrotechnics with the desired working results. The use of PVC is effective in inhibiting the burning rate of yellow pyrotechnics at 1.76-15%, where the addition of PVC fraction above that number results in a burning rate that tends to remain at a value of fewer than 2.29 g/s [18] but with a decrease in intensity and a spike in the dominant wavelength that produces an orange color.

Ideally, yellow color dominance could be achieved at PVC fractions ranging from 0-12.82% because, at this point, it still produces wavelengths of 583-589 nm [13] with a striking yellow color. In contrast, the addition of more PVC continued to trigger a decrease in intensity until the limit at 263 lux [19], which was at 10.21% additive composition. Thus, these three parameters indicate that PVC additives can be used at a composition of 1.76-10.21% of the flare mixture used.

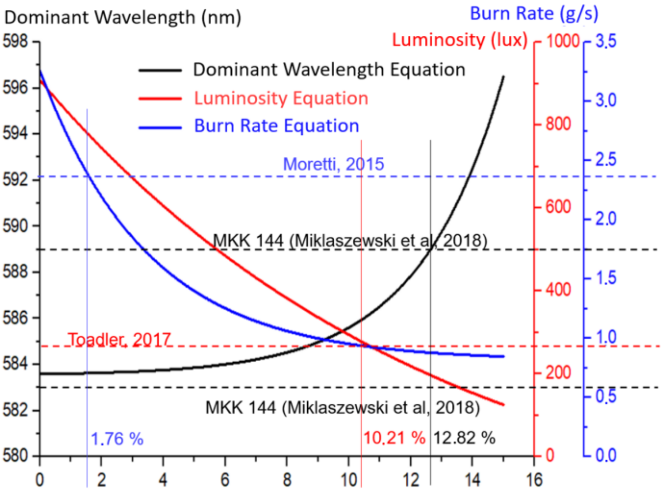

Fig. 5. Optimum fraction of PVC additives in pyrotechnics mixture

CONCLUSION

The effects of PVC additives on the performance, including light intensity, emission spectrum, and burning rate, were successfully observed. Pyrotechnic samples without PVC showed an emission spectrum of 577-585 nm, a luminosity of 723-1184 lux, and a burning rate of 3.22-3.31 g/s. Increasing the amount of PVC additive to 1.5 g showed an emission with a wavelength of 596-597 nm, a decrease in luminosity from 91-183 lux, and a slower burning rate of 0.72-0.88 g/s. The equation of each PVC mass composition of the pyrotechnic mixture produced 3 parameter equations, where with a fraction value of x of 0-15%, it produced an equation for the dominant wavelength $y = 0.05\ e^{(x/2.73)} + 583.53$, light intensity $y = 991.55\ e^{(-0.13x)}$, and burning rate with the equation $y = 2.55\ e^{(-x/0.36)} + 0.90$. Therefore, PVC additives were most beneficial for slowing down the burning rate with the side effect of reducing the brightness of the yellow color and its light intensity. The use of PVC could be applied effectively to the fraction of 1.76-10.21%, where at that value, the dominant wavelength was still in the range of 583-589 nm and was actively able to slow down the burning rate of pyrotechnic materials

SUPPORTING INFORMATION

There is no supporting information in this paper.

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CONFLICT OF INTEREST

The authors have no conflict of interest in this publication.

AUTHOR CONTRIBUTIONS

G and AM conceptualized the research and finalized the manuscript. AB, SAW, EP, and SAW conducted the experiment, analyzed data, wrote, and revised the manuscript. All authors agreed to the final version of this manuscript.

REFERENCES

[1] Ambekar A., Kim M., Lee W.H., & Yoh J.J. 2017. Characterization of display pyrotechnic propellants: Burning rate. *Appl. Therm. Eng.* 121. 761–767. doi: 10.1016/j.applthermaleng.2017.04.097.

[2] Conkling J.A. & Mocella C.J. 2019. *Chemistry of Pyrotechnics: Basic Principles and Theory, Third Edition.* doi: 10.1201/9780429262135.

[3] Sadek R., Kassem M., Abdo M., & Elbasuney S. 2017. Novel yellow colored flame compositions with superior spectral performance. *Def. Technol.* 13(1). 33–39. doi: 10.1016/j.dt.2016.12.001.

[4] Moretti J.D., Sabatini J.J., & Poret J.C. 2014. High-performing red-light-emitting pyrotechnic illuminants through the use of perchlorate-free materials. *Chem.-A Eur. J.* 20(28). 8800–8804. doi: 10.1002/chem.201402654.

[5] Huang Z., Xu S., Chen X., Wang M., Yuan H., Zhao H., & Zhang Y. 2021. Construction of a novel barium-free green-light emitting illuminant based on boron carbide. *Propellants, Explos. Pyrotech.* 46(9). 1480–1488. doi: 10.1002/prep.202100038.

[6] Ambekar A., Kim M., & Yoh J.J. 2017. Characterization of display pyrotechnic propellants: Colored light. *Appl. Therm. Eng.* 110. 1066–1074. doi: 10.1016/j.applthermaleng.2016.09.040.

[7] Juknelevicius D., Karvinen E., Klapötke T.M., Kubilius R., Ramanavicius A., & Rusan M. 2015. Copper(I) bromide: an alternative emitter for blue-colored flame pyrotechnics. *Chem.-A Eur. J.* 21(43). 15354–15359. doi: 10.1002/chem.201502752.

[8] Sabatini J.J. 2018. A review of illuminating pyrotechnics. *Propellants, Explos. Pyrotech.* 43(1). 28–37. doi: 10.1002/prep.201700189.

[9] Blair L. 2015. Mixing and characterisation of multi-component materials for pyrotechnic applications. *Doctoral Disertation.* University of Southampton.

[10] Biegańska J. & Barański K. 2022. Experiments with pyrotechnic compositions based on a mathematical model: part II pyrotechnic compositions producing an acoustic effect with optimum properties. *Energies.* 15(3). 794. doi: 10.3390/en15030794.

[11] Keller F. & Schragen C. 2021. Determination of particulate matter emission factors of common pyrotechnic articles. *Propellants, Explos. Pyrotech.* 46(5). 825–842. doi: 10.1002/prep.202000292.

[12] Wang F., Pan S., Zhang P., Fan H., Chen Y., & Yan J. 2018. synthesis and application of phosphorus-containing flame retardant plasticizer for polyvinyl chloride. *Fibers Polym.* 19(5). 1057–1063. doi: 10.1007/s12221-018-7493-8.

[13] Dilger J.M., Miklaszewski E.J., Papenmeier D.M., Thoreson K.M., Fedick P.W., Coleman J.E., & Bohrer B.C. 2018. Pyrolysis/GC/MS as a method to rapidly profile pyrotechnic formulations for objectionable gaseous emissions. *ACS Sustain. Chem. Eng.* 6(12). 16990–16999. doi: 10.1021/acssuschemeng.8b04342.

[14] Singh H., Somayajulu M.R., & Bhaskara Rao R. 1989. A study on combustion behavior of magnesiumsodium nitrate binary mixtures. *Combust. Flame.* 76(1). 57–61. doi: 10.1016/0010-2180(89)90077-1.

[15] Lloret A.T., Sendra S., Lloret J., Louis Cereceda M., & Alba J. 2017. Impact of pyrotechnics over the architectonic heritage. *J.*

Sensors. 214975. doi: 10.1155/2017/7214975.

[16] Sabatini J.J., Nagori A. V., Latalladi E.A., Poret J.C., Chen G., Damavarapu R., & Klapötke T.M. 2011. Applications of high-nitrogen energetics in pyrotechnics: Development of perchlorate-free red star M126A1 hand-held signal formulations with superior luminous intensities and burn times. *Propellants, Explos. Pyrotech.* 36(4). 373–378. doi: 10.1002/prep.201100023.

[17] Sabatini J.J., Koch E.C., Poret J.C., Moretti J.D., & Harbol S.M. 2015. Chlorine-free red-burning pyrotechnics. *Angew. Chemie - Int. Ed.* 54(37). 10968–10970. doi: 10.1002/anie.201505829.

[18] Moretti J.D., Sabatini J.J., Poret J.C., & Gilbert R.A. 2015. Development of sustainable, epoxy-bound mg/nano3 compositions for the u.s. army's 40 mm yellow illuminant flares. *ACS Sustain. Chem. Eng.* 3(9). 2232–2236. doi: 10.1021/acssuschemeng.5b00508.

[19] Toader G., Rotariu T., Rusen E., Tartiere J., Esanu S., & Zecheru T. 2017. New solvent-free polyurea binder for plastic pyrotechnic compositions. *Mater. Plast.* 54(1). 22-28. doi: 10.37358/MP.17.1.4777.