



## Enhanced propellant performance via environmentally friendly curable surface coating



Thelma Manning<sup>a,\*</sup>, Jeffrey Wyckoff<sup>a</sup>, Kenneth Klingaman<sup>a</sup>, Viral Panchal<sup>a</sup>, Eugene Rozumov<sup>a</sup>, John Bolognini<sup>a</sup>, Ming Wang Young<sup>b</sup>, Subhash Patel<sup>b</sup>

<sup>a</sup> US Army RDECOM ARDEC, Picatinny Arsenal, NJ, USA

<sup>b</sup> Polymer Processing Institute, Newark, NJ, USA

### ARTICLE INFO

#### Article history:

Received 30 January 2017

Accepted 25 April 2017

Available online 27 April 2017

### ABSTRACT

Surface coating of granular propellants is widely used in a multiplicity of propellants for small, medium and large caliber ammunition. All small caliber ball propellants exhibit burning progressivity due to application of effective deterrent coatings. Large perforated propellant grains have also begun utilizing plasticizing and impregnated deterrent coatings with the purpose of increasing charge weights for greater energy and velocity for the projectile. The deterrent coating and impregnation process utilizes volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) which results in propellants that need to be forced air dried which impacts air quality. Propellants undergo temperature fluctuations during their life. Diffusion coefficients vary exponentially with variations in temperature. A small temperature increase can induce a faster migration, even over a short period of time, which can lead to large deviations in the concentration. This large concentration change in the ammunition becomes a safety or performance liability. The presence of both polymeric deterrents and nitroglycerin (NG) in the nitrocellulose matrix and organic solvents leads to higher diffusion rates. This results in continued emissions of VOCs and HAPs. Conventional polymers tend to partition within the propellant matrix. In other words, localized mixing can occur between the polymer and underlying propellant. This is due to solvent induced softening of the polymer vehicle over the propellant grain. In effect this creates a path where migration can occur. Since nitrate esters, like NG, are relatively small, it can exude to the surface and create a highly unstable and dangerous situation for the warfighter. Curable polymers do not suffer from this partitioning due to “melting” because no VOC solvents are present. They remain surface coated. The small scale characterization testing, such as closed bomb testing, small scale sensitivity, thermal stability, and chemical compatibility, will be presented. The 30 mm gun demonstration firing data at hot, cold, and ambient temperatures will also be presented.

Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

### 1. Introduction

The objective of the research effort is to replace the current solvent based wet deterrent and impregnation coating technology, currently used in propellant production, with the environmentally friendly novel Light Emitting Diode Ultra-Violet (LED-UV) cured solvent-less advanced surface coating technology. This research effort work is to explore the use of LED UV curable polymers as deterrent coating materials, which do not suffer from this

partitioning due to “melting” because of the highly adjustable and attainable network structure. The additional objectives are to increase performance without increasing maximum breech pressure by the slowed and inhibited burning and obtain progressivity at the grain and charge levels. The surface coating objective is also to achieve a flat temperature coefficient by having a low glass transition temperature ( $T_g$ ) of coating materials. The low  $T_g$  can prevent the initiation, disrobing, cracking, ablation, penetration, and coating separation at cold temperatures. The improved mechanical properties across the ballistic temperature range are expected to improve Insensitive Munitions (IM) characteristics against thermal and spall threats. The crosslink LED UV coating polymer structure can inhibit/reduce migration which can prevent plasticizer migration and degradation of performance resulting from migration. This

\* Corresponding author.

E-mail address: [thelma.g.manning.civ@mail.mil](mailto:thelma.g.manning.civ@mail.mil) (T. Manning).

Peer review under responsibility of China Ordnance Society.

migration results in large concentration changes in ammunition which becomes a safety or performance liability [1]. In addition, the recent advances in high power LED's ensures an abundant commercial availability of the LED UV light source. This makes it possible to greatly reduce the production cost by minimizing the production space requirements and energy usage, as well as, generating virtually no waste stream.

## 2. Experimental

### 2.1. LED UV coating formulation development

There are four major attributes of the UV curable monomers which contribute to the final coating performance. They are: functionality, chemical backbone, chemical structure and molecular weight. The formulation development focused on two basic components in the make up of the LED UV curable compositions: Monomer and/or Reactive Diluents and Photo Initiators (PI). An increase in the functionality of the monomers usually speeds up the light curing reactions. The concentration of the photoinitiator was varied to achieve a dramatic effect on desired properties of LED UV cured coating. Monomer and Reactive Diluents utilized were: mono-functional i.e. SR256, 2 (2-Ethoxyethoxy) Ethyl Acrylate, di-functional, tri-functional (i.e. SR4942 (2 Ethoxy ethoxy) Ethyl Acrylate and SR 9012: Tri-functional acrylate ester) and tetrafunctional (i.e. SR 494 Ethoxylated (4) Pentaerythritol Tetraacrylate) monomers to achieve a three dimensional network. The functionalized monomers used are lower in viscosity, which facilitates a coating application with improved surface wetting, leveling and offering widely attainable physical properties derived from numerous available chemical structures. Reactive diluents in a LED UV curable formulation played a key role. It is a mono-functional liquid; and affected both cure speed and the extent of polymerization, as well as the properties of the final product. Increasing the monomer functionality leads to higher cure speed, higher  $T_g$ , higher crosslink density, higher shear strength, and greater chemical and thermal resistance, but lower flexibility and low conversion.

A photoinitiator (PI) is a compound that, upon absorption of light, undergoes a photoreaction and produces reactive species of free radicals. This induces cross linking between the unsaturated carbon to carbon double bonds (C=C) sites of monomers/oligomers. This accomplishes the cure process to generate polymer C-C bonds. Thus, PI transforms the physical energy of light into suitable chemical energy in the form of reactive intermediates. The photoinitiator package was optimized for a given coating thickness and LED UV dosage. The formulation development focused on formulating surface cure PI with excellent solubility and sound resistance to oxygen poisoning. At the same time it possesses suitable photon sensitivity to the selected LED UV wavelengths from 385 nm to 415 nm. Five different types of photoinitiators with concentrations from 0.01 g/l to 0.2 g/l were investigated to achieve an optimized LED UV absorbance as a function of light wavelengths [3].

Several LED UV coating formulations were developed, optimized and characterized. The formulation characterization consisted of using the Photo Differential Scanning Calorimetry (Photo-DSC) and LED UV Coating Droplet Diameter Measurement for Wettability. The optimized light cured formulations were then applied by coating them on the surface of an inert simulant. This incorporated a cellulose acetate binder with calcium carbonate powder and an energetic single base propellant (AFP-001) grains as the substrates and processed using the Mini Glatt Fluidized bed to be discussed in the next section.

### 2.2. Processing LED UV coating formulation

The processing consisted of using Ultra Violet (UV) curable coatings employing solvent-less and low viscosity reactive liquids. They can be applied to selected substrates, and converted into a solid adherent film within a fraction of a second when exposed to LED UV light [5]. Fig. 1(a) is a remotely operated Fluidized Bed Coater fitted with an explosion proof UV light source (medium density mercury lamps); its operating mechanism is illustrated in Fig. 1(b). The coating of a UV composition on a propellant surface in the fluidized bed could be described in four elementary steps, (1) Fluidization of propellant grains (2) Atomization of UV liquid through the spray nozzle, (3) Wetting fluidized propellants with UV liquid droplets, and formation of coating layer via spreading, (4) Rapid curing of UV liquid when exposed to the UV light through the glass window.

### 2.3. Vacuum thermal stability testing (VTS)

Prior to processing, compatibility tests were conducted to determine if the UV light cured monomers were compatible with nitrocellulose binder, plasticizer, and stabilizer in the AFP-001 propellant substrate. Using a Perkin Elmer Pyris 1 Differential Scanning Calorimeter (DSC), samples were run through temperature scans according to STANAG 4147. Temperature scans were performed from 50 °C to 350 °C. Samples were sealed in aluminum pans and run in duplicate. A decomposition peak temperature shift of 4 °C or less was deemed compatible. Any shift towards a lower peak temperature of the materials was deemed to exhibit some degree of incompatibility, with the magnitude of the shift corresponding to the degree of incompatibility. A peak temperature shift of more than 20 °C indicates incompatibility. Peak temperature shifts between 4 °C and 20 °C indicate partial or potential incompatibility, in which case Vacuum Thermal Stability (VTS) testing was required to confirm or deny incompatibility. This was done in accordance with STANAG 4556 ED.1 (Explosives: Vacuum Stability Test). This standard testing procedure measures the stability of an explosive at an elevated temperature under vacuum. The candidate explosive and materials are tested alone as control subjects. The explosive is then mixed with each individual material and tested. The reactivity (compatibility) is then determined by comparing the gas evolved by the candidate explosive control, the material control, and the mixture. The materials were tested for 40 h at 100 °C.

The LED UV light cured monomers that passed the compatibility testing were then surface coated on the AFP-001 propellant substrate and the actual mixes were characterized for incompatibility via Vacuum Thermal Stability (VTS). The propellant surface coating formulations that passed the VTS test were then scaled up to 150 g surface coating. All of the new UV light cured monomers have shown compatibility with NC, plasticizer and stabilizer incorporated into the AFP-001 propellant formulation, according to both the DSC and VTS tests. The VTS criteria used are listed in Table 1.

### 2.4. Closed bomb test

After the VTS analysis of those ingredients that proved to be compatible with AFP-001 propellant and plasticizer, several 150 g propellant formulations were surface coated using the UV Fluidized Bed Coater at ARDEC. They were then weighed out, grain dimensioned and density measured for closed bomb analysis at 21 °C. The closed bomb test is designed to determine linear burning rates of energetic compositions at elevated pressures. The capacity for closed bomb used in this testing was 200 cc. Three 20-g propellant

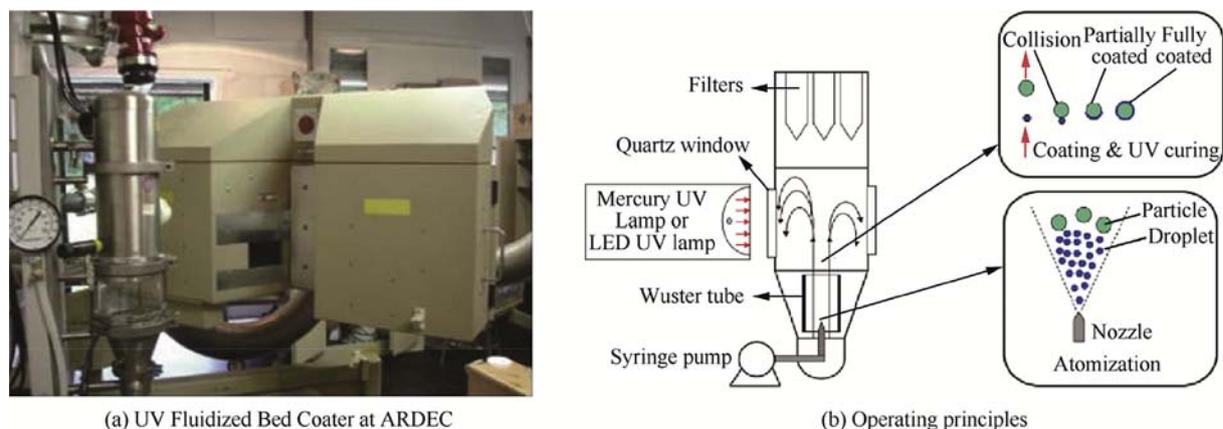


Fig. 1. UV Fluidized bed coater at ARDEC and operating principles.

Table 1  
VTS criteria.

Extent of reactivity excess gas/ml	Degree of reactivity
0.0–3.0	Compatible
3.0–5.0	Marginally compatible
5.0 & above	Incompatible

samples were tested for each gun propellant formulation using a loading density of 0.10. The propellant grains were single perforation (0.006" Perf. diameter) with an outer diameter of 0.072" and a length of 0.088". All tests generated pressures in excess of 15 KSI. The closed bomb test results were analyzed and plotted. Many of the new LED UV coating formulations have pressure exponents less than 1, like that of JA2. JA2 is a legacy propellant that has acceptable propellant characteristics. Burn rates in many of the surface coated AFP-001 with LED UV coating formulations such as the PAP-8604, 8605 and 8606 lot were identified as Picatinny Arsenal Propellant lots RDD14H-00194, RDD14H-00195, and RDD14H-00196.

Using the propellant thermochemical properties, burn rates and pressure exponent, IBHVG2 interior ballistics code was employed to predict the theoretical velocities of these novel surface coated AFP-001 with LED UV coating formulations such as the PAP-8604, 8605 and 8606 using a single perforated grain geometry.

### 3. Results and discussion

#### 3.1. LED UV coating formulation development

For the approach, several Photoinitiators, monomers, reactive diluents and surface tension modifiers for LED UV Curing were investigated, selected and characterized.

#### 3.2. Characterization

##### 3.2.1. Evaluation of photo-initiators (PI)

Photo-initiators are molecules that absorb the energy of light and act as donors by transferring this energy to acceptor molecules [5,6]. The molecules that receive the energy may in turn undergo reactions, such as polymerizations, isomerizations, couplings and others. A good photo-initiator, therefore, is not only a molecule that readily absorbs light energy, but also one that readily transfers complexes in molecules. The photo-initiators investigated were organic compounds, that upon absorbing light energy, formed polymerization initiating species. Such species were free radicals. These molecules functioned as photo initiators. The PI used were

mostly benzophenone and ketones. They absorb light energy and transfer it to another molecule and form  $\alpha$  -  $\beta$ -cleavage to form initiating species when irradiated with light of the appropriate wavelength. Five free radical photoinitiators were investigated and characterized. The UV absorbance spectra of the free radical photoinitiators are shown in Figs. 2–6.

UV-VIS spectra of the five photo-initiators evaluated are shown in Figs. 2–6. Based on the UV-VIS spectrum, KIP-100 showed 0.4 UV absorbance at 350–400 nm wavelength at the concentration of 0.2 g per liter when compared to the other photo initiators evaluated.

Table 2 shows the LED UV coating formulations evaluated for heat of reactions and percent conversion using the four different photo-initiators (see Table 3).

Each LED UV coating formulations were identified as Series 1,2,3, and 4. From the typical photo-DSC results as shown in Fig. 7, the Heat of Reaction and percent conversions were determined for each LED UV coating formulations.

Fig. 8 showed that series 3 from Table 2 has the slowest reaction and had the slowest per cent conversion (see Fig. 9).

##### 3.2.2. Changes in contact angle (wettability)

After the photo initiator evaluations were completed, the wettability of the LED UV coating formulations were determined. An inert substrate using Cellulose Acetate Butyrate (CAB) binder with inert filler was used. The amount of 20 ul of the formulation mixture was applied on the CAB substrate plate. After 2 min, the diameters of the droplets were measured by caliper as shown in Fig. 10.

The contact angles of the monomers on the CAB substrate surfaces changes depend on the type of the acrylates and the degree of functionalization. Tables 4–6 below, show the effects of photoinitiators and reactive diluents on the wettability of various formulations. From Tables 4–7, it can be seen that the contact angle may increase or decrease in diameter with the addition of the photo initiator and reactive diluents [5]. Table 7 shows the formulations selected for Photo-DSC study. The wettability of UV coating formulation is ranked the best when the droplet diameter is the largest in size when compared to the other LED UV coating formulations when the photoinitiator and reactive diluents are added in the UV coating formulations.

The recommended LED UV coating formulations shown in Table 8 were selected based on the rate of reaction/heat of reactions and per cent conversions shown in Figs. 11 and 12 (a) and (b). After the selection of the LED UV coating formulation shown in Table 8, for the proof-of-concept, the initial UV coating formulation

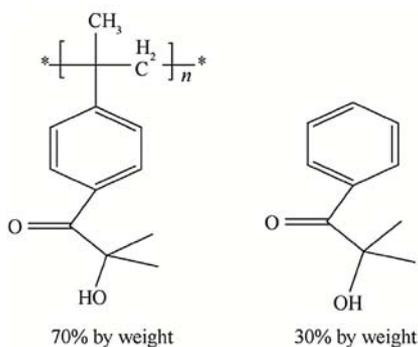


Fig. 2. Esacure KIP 100F.

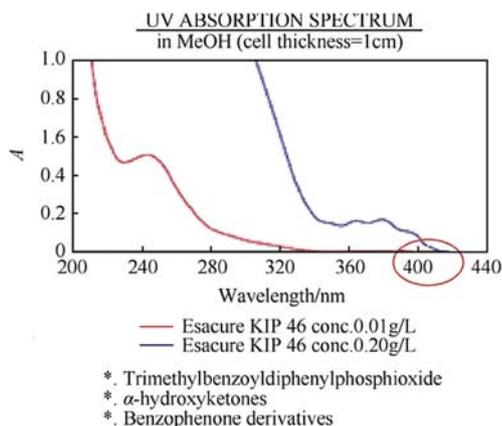
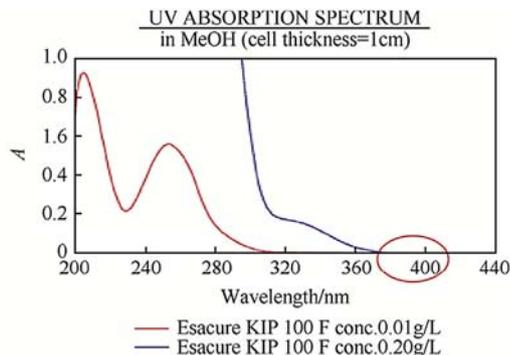


Fig. 3. Esacure KTO 46.

development effort started with an inert simulant consisting of an inert filler and Cellulose Acetate Binder (CAB). The UV coating formulation, concentration and processing parameters were varied as shown in Fig. 13. The surface coating showed a blotchy coat and not uniform on CAB surface when seen under a microscope as shown in Fig. 14. Although the LED UV coating were not uniformly spread on the inert propellant grain surface, the results gave us a direction to modify the LED UV coating formulations and optimized the processing parameters to achieve better wettability on the propellant surface.

### 3.2.3. Glass transition temperature

The glass transition temperatures ( $T_g$ ) of the LED UV coating

formulations listed in Table 8 were determined. The temperature sweep showed a  $T_g = -31.50^\circ\text{C}$  with PAP-8606 from  $-60$  to  $+50^\circ\text{C}$  as shown in Fig. 15(c). There were no visible  $T_g$  in that range for the other samples, PAP-8604 and PAP-8605 LED UV coating formulations as shown in Fig. 15 (b) and (c), respectively. These other samples could have a  $T_g$  below  $-60^\circ\text{C}$  but our instrument is only accurate to  $-60^\circ\text{C}$ .

### 3.2.4. LED UV surface coating with energetic AFP-001 propellant

The UV surface coating formulations down-selected, listed in Table 8, was processed using the fluidized bed UV coater previously shown in Fig. 1 using the energetic AFP-001 propellant substrate. The LED UV coated and uncoated AFP-001 propellant grains shown in Fig. 15 were characterized by closed bomb testing. Burn rates were determined by closed bomb analysis. Samples were then weighted out, grain dimensioned and density measured for closed bomb analysis at  $21^\circ\text{C}$ . The closed bomb test is designed to determine linear burning rates of energetic compositions at elevated pressures. The closed bomb was a 200 cc vessel filled to a 0.1 g/cc loading density with AFP-001 single perforated grains. Three 20-g propellant samples were tested for each LED UV coated formulations. The uncoated AFP-001 propellant grains were single perf (0.006 inch perf. diameter with an outer diameter of 0.083 inch and a length of 0.096 inch). All tests generated pressures in excess of 15 kpsi. For the down-selected LED UV coating formulations, one test temperatures were utilized:  $21^\circ\text{C}$ . The closed bomb test results were plotted and are shown in Figs. 18–24. The uncoated AFP-001 single perforated propellant has a digressive linear burning rate which followed the form function geometry. The new LED UV surface coated AFP-001 propellants have pressure exponents less than 1. The apparent burn rates in many of the new LED UV surface coated AFP-001 propellants appear to burn linearly. The burn rates

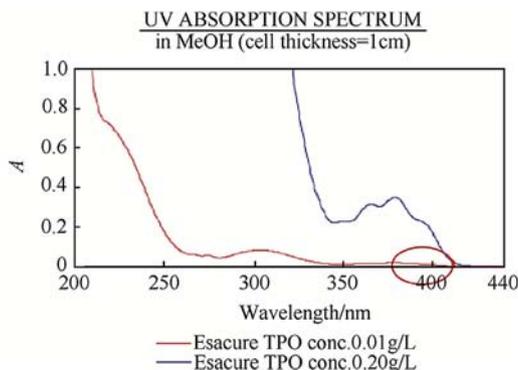
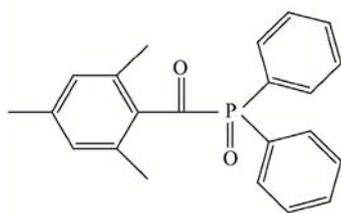


Fig. 4. Esacure TPO.

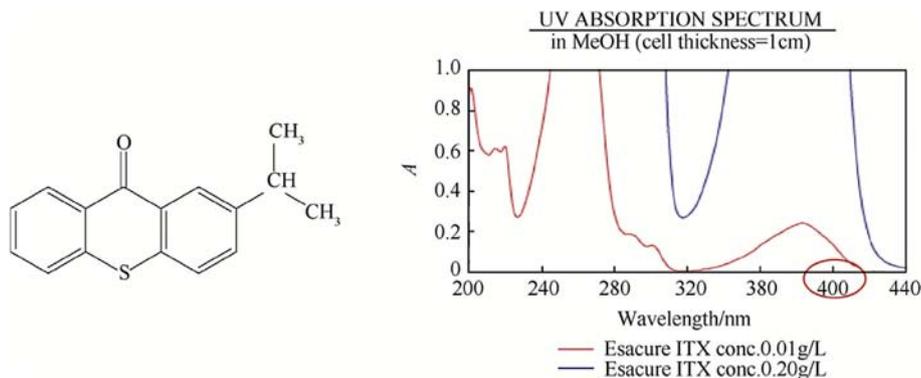


Fig. 5. Esacure ITX.

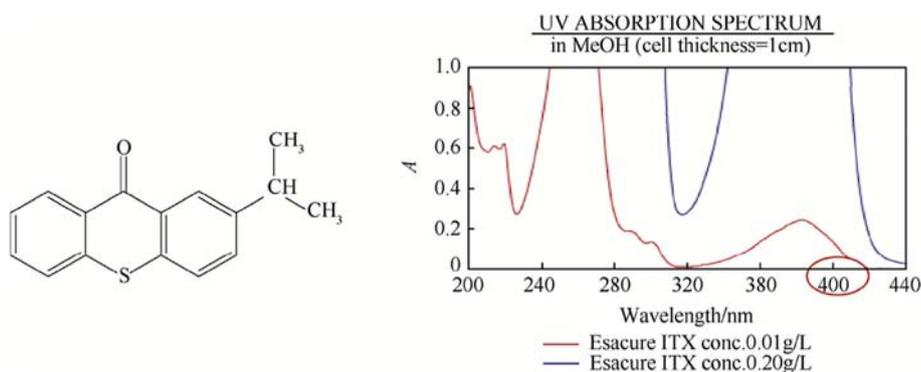


Fig. 6. Bis (2,4,6 - trimethylbenzoyl) - phenylphosphineoxide.

Table 2  
UV LED chemical compositions.

Formulation#	Compositions
1	Esacure KIP 100F/SR344/SR494(5:47.5/47.5)
2	Esacure KTO 46/SR344/SR494(5:47.5/47.5)
3	Esacure ITX/SR344/SR494(5:47.5/47.5)
4	Esacure TOP/SR344/SR494(5:47.5/47.5)

pressure coefficients and pressure exponents are tabulated in Table 9. LED UV coating formulations 8606-4 and 8606-2 in AFP-001 burn much faster compared to all the other LED UV coating formulations shown in Fig. 25.

PAP-8604-4 burns much slower when compared to the baseline uncoated AFP-001 and the other LED UV coated formulations 8604-2, 8605-4, and 8605-2, as shown in Fig. 25.

To provide a visual comparison of the relative performance, the dynamic vivacity has been reviewed. One should note that there are

three parts to the propellant vivacity curve. The first is sensitive to the rate of flame spread. The third is the result of flame spread time and splintering, spreading web burnout in time and therefore pressure. The middle part of the curve has a slope that is a function of the instantaneous surface area to original propellant volume, and composition. The characteristic slope starts when all the propellant surface area is inflamed. The end of this slope is easier to define when dealing with progressive geometries. The comparison of vivacity curves for the three LED UV coating formulations candidates are shown in Figs. 18(b)–24(b). Since the LED UV coating formulations are experimental, an inspection of the vivacity curves was made to determine anomalous effects [4,7]. Vivacity is an expression of the mass rate of combustion or the rate of gas generation [4,7]. Under the assumption of spatially constant propellant composition and LED UV coating formulations, a change in vivacity indicates a change in available surface area. The vivacity versus normalized pressures were plotted in Fig. 26 to make a qualitative method to ascertain the nonstandard behavior of the propellant

Table 3  
Kinetic data from four UV coating formulations.

Time/s	Conversion S1/%	Conversion S2/%	Conversion S3/%	Conversion S4/%
0	0	0	0	0
10	90.55	94.08	53.56	92.76
20	97.92	98.66	78.28	97.02
30	99.90	99.91	91.35	99.34
40	100	100	97.18	100
50	100	100	99.27	100
60	100	100	99.96	100
70	100	100	100	100

S1-Esacure KIP 100 F; S2-Esacure KTO 46; S3-Esacure ITX; S4-Esacure TPO.

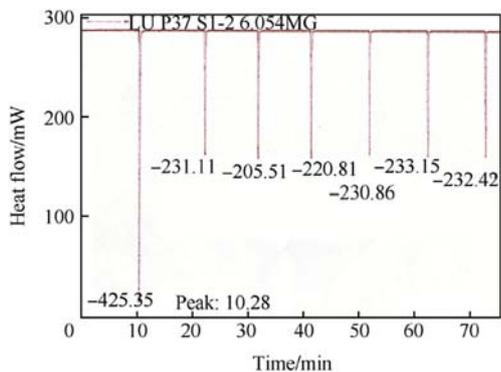


Fig. 7. Typical Photo DSC results (Formulation LU P-37).

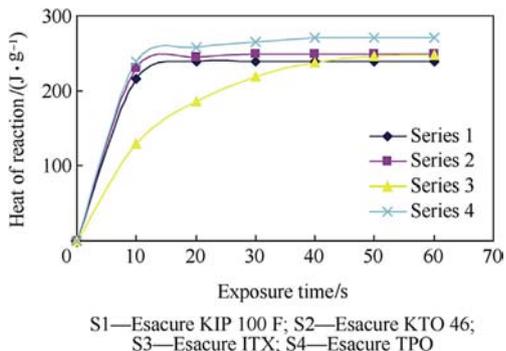


Fig. 8. Kinetic data from Photo-DSC.

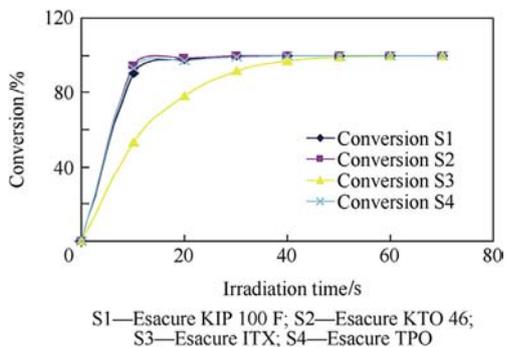


Fig. 9. % Conversion from Photo-DSC and Kinetic curves for UV LED curing.

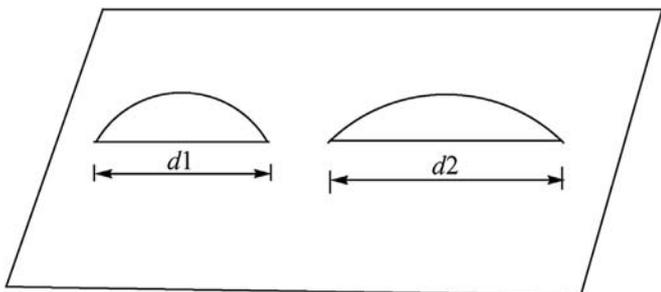


Fig. 10. 20  $\mu$ l of the formulation mixture was applied on the CAB plate, after 2 min, diameters of the droplets were measured by caliper.

with varying LED UV coating formulations. In these plots, the dynamic vivacity has been calculated and plotted against the

Table 4  
Effect of the photo-initiator.

	Formulation	Diameter/mm
LU-67-1	SR344/SR494(50/50)	10.26
LU-67-2	SR344/SR494/KIP 100F(47.5/47.5/5)	9.77
LU-67-6	SR9012	10.01
LU-67-5	SR9012/KIP 100F(95/5)	10.36

Table 5  
Effect of reactive diluent SR 506A.

	Formulation	Diameter/mm
LU-67-7	SR9012/SR506/KIP 100F(85/10/5)	10.43
LU-67-8	SR344/SR494/KIP 100F(42.5/42.5/10/5)	10.33
LU-67-9	SR494/SR9012/KIP 100F(47.5/47.5/5)	9.88
LU-67-10	SR494/SR9012/SR506/KIP 100F(42.5/42.5/10/5)	11.27

Table 6  
Effect of reactive diluent SR 256.

	Formulation	Diameter/mm
LU-67-11	SR9012/SR256/KIP 100F(85/10/5)	10.55
LU-67-12	SR344/SR494/SR256/KIP 100F(42.5/42.5/10/5)	10.40
LU-67-13	SR494/SR256/KIP 100F(95/5)	10.10
LU-67-14	SR494/SR9012/SR256/KIP 100F(42.5/42.5/10/5)	11.00

Table 7  
Formulations for Photo-DSC stud.

	Formulation	Diameter/mm
LU-67-2	SR344/SR494/KIP 100F(47.5/47.5/5)	9.77
LU-67-9	SR494/SR9012/KIP 100F(47.5/47.5/5)	9.88
LU-67-10	SR494/SR9012/SR506/KIP 100F(42.5/42.5/10/5)	11.27
LU-67-14	SR494/SR9012/SR256/KIP 100F(42.5/42.5/10/5)	11.00

Table 8  
Recommended formulations for coating test.

	Formulation
LU-67-10(8604)	SR494/SR9012/SR506/KIP100F
LU-67-14(8605)	SR494/SR9012/SR256/KIP100F
LU-67-2(8606)	SR494/SR344/KIP100F

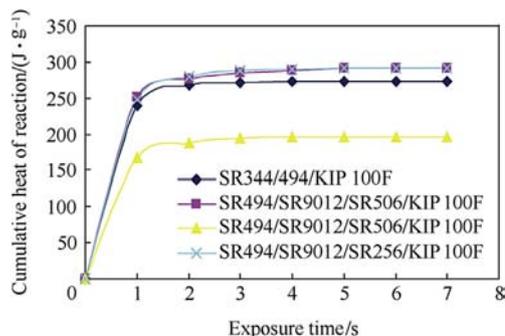


Fig. 11. Cumulative heat of reaction of UV coating formulations.

normalized pressure in the closed bomb ( $P/P_{max}$ ). The plots clearly show the influence on the burn speed for the three LED UV coating formulation candidates. Higher vivacity values are an indicator of higher gasification rates. Assuming the apparent burn rates are constant, the changes in the gasification are due to an increase in

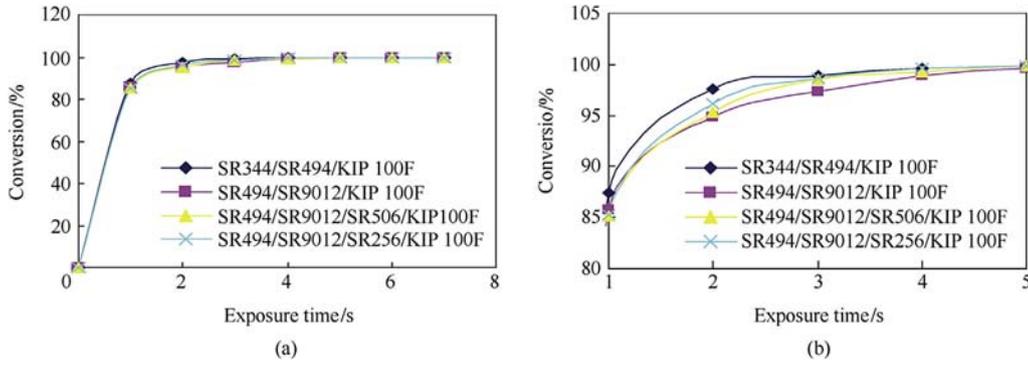


Fig. 12. Per cent conversion of UV coating formulations.



Fig. 13. UV Curable coatings with varying concentration (0.5%, 0.6%, 1%, 2%,4%,6% on inert CAB substrate.



Fig. 14. Blotchy coat on Surface of inert CAB substrate.

the burning surface area. The LED UV coating formulation 8606-4 and 8606-2 have a much higher vivacity followed by in decreasing order 8604-2, 8605-2, AFP-001 and 8604-4 as shown in Fig. 26. LED UV coating formulations 8606-4 and 8606-2 apparent burn rates were the highest when compared to the other LED UV coating formulations shown in Fig. 25. The breakup of the LED UV surface coating were exposing fresh propellant surface area resulting in higher apparent burn rates and greater vivacity, resulting in the propellant progressivity as demonstrated by the LED UV coating formulations 8606-4 and 8606-2.

Using the data obtained from this test, the burn rate can be predicted using the Vieille's burn rate law shown in equation (1), wherein P is the pressure in the chamber,  $\alpha$  is the burn rate coefficient, and  $\beta$  is the burn rate pressure exponent [2,4].

$$\text{Burn Rate} = \alpha P^\beta \tag{1}$$

This burn rate was then used in the Interior Ballistic High

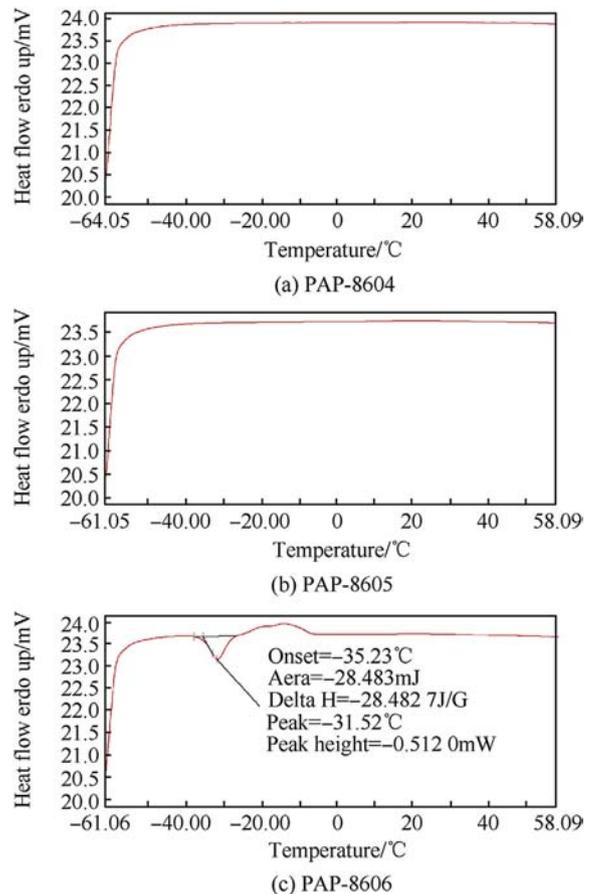


Fig. 15. Glass transition temperatures(Tg) of the LED UV coating formulations PAP-8604, PAP-8605 and PAP-8606.



**Fig. 16.** AFP-001 AND LED UV Surface Coated Energetic Propellant AFP-001 (Uncoated Grain Dimensions: Length = 0.096 inch, Diameter = 0.083 inch, Perf Diameter = 0.006 inch, Average Web Size = 0.038 inch).

Velocity Gun version 2 (IBHVG2) code to model ballistic performance. This code was utilized to determine the ballistic grain geometry and web dimensions needed for 30 mm gun firings.

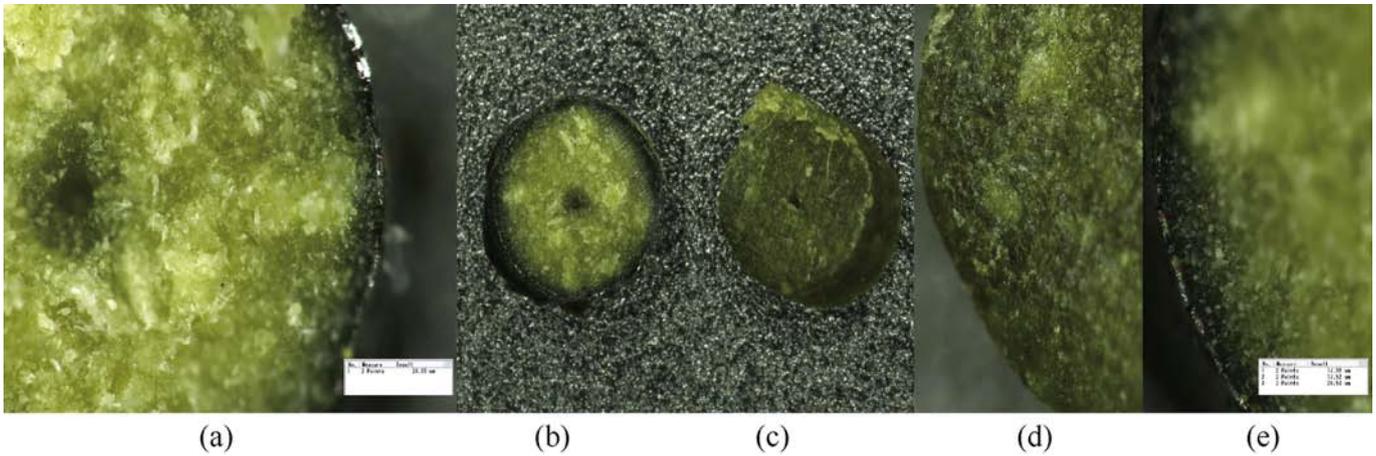
For the ballistic performance test, AFP-001 propellant surface coated with 2% PAP-8604 LED UV coating formulation was used. The propellant AFP-001 is an Air Force fielded propellant. Its ballistic behavior with 2% PAP-8604 LED UV surface coating

formulation is unknown in the 30 mm gun based on the IBHVG2 predictions. ARDEC surface coated 3000 g of single perforated AFP-001 is shown in Fig. 16. In Fig. 17, the uncoated, and 2% and 4% AFP-001 LED UV coating formulation surface coated on the AFP-001 propellant is presented. The 2% PAP-8604 LED UV coating formulation was used in the 30 mm × 173 mm sub-scale ballistic performance and sensitivity tests.

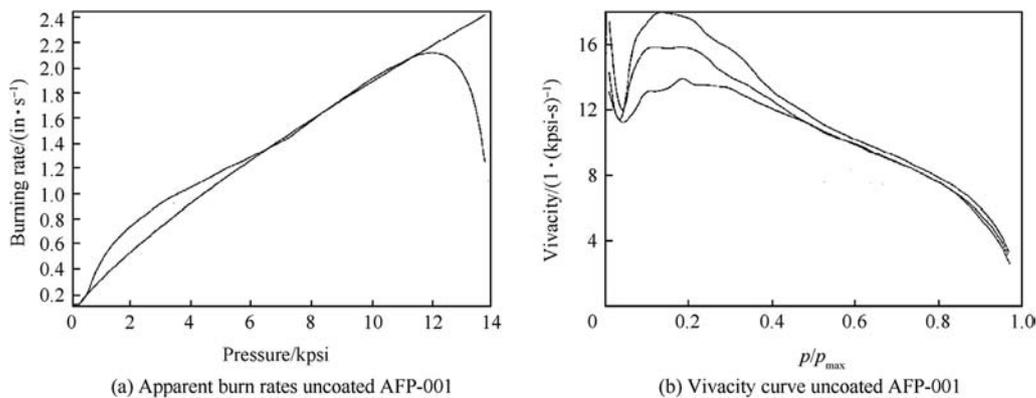
**3.2.5. Gun firing**

After the LED UV surface coating process and preliminary closed bomb tests were completed, ballistic tests were conducted. A blend of uncoated and coated propellants was shot in an effort to meet the ballistic targets. The ballistic testing was conducted across the operating temperature envelope required by the cartridge specification, -60 °F, 70 °F and +145 °F.

For the first iteration 30 mm sub-scale gun firing (30 mm × 173 mm), the LED UV coating formulation PAP-8604-2 was selected for the initial proof of concept. A final blend configuration was chosen for a final set of ballistic tests. The final AFP-001 propellant blend was an uncoated and LED UV coated blend. Final ballistic results are shown in Fig. 27. The muzzle velocities of AFP-001 surface coated with LED UV coating formulation PAP-8604-2 were comparable to the uncoated AFP-001 as shown in Fig. 28 except at hot temperatures. The muzzle velocity of LED UV coating formulation PAP-8604-2 at hot temperatures was higher than the uncoated AFP-001. The Breech Pressures as shown in



**Fig. 17.** (a): LED UV Coated Surface Coated AFP-001 (PAP-8604-2) live propellant pellet with 2% coating material at a flow rate of 0.25 g/minute, (b) Microscope photo of the cross-section area of coated propellant and (c) uncoated propellant single perforated grain. (d) Uncoated AFP-001 propellant surface and (e) thickness of surface coated AFP-001 propellant.



**Fig. 18.** Apparent burn rates uncoated AFP-001 and vivacity curve uncoated AFP-001.

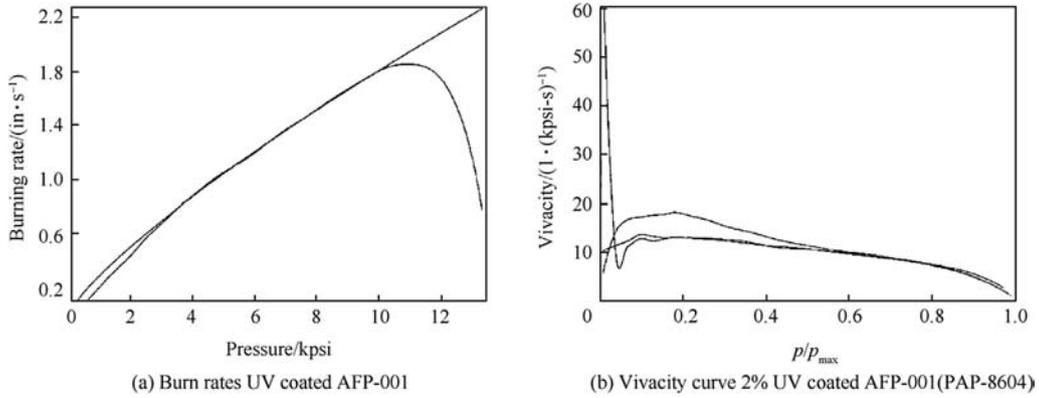


Fig. 19. Burn rates UV coated AFP-001 and vivacity curve 2% UV coated AFP-001(PAP-8604).

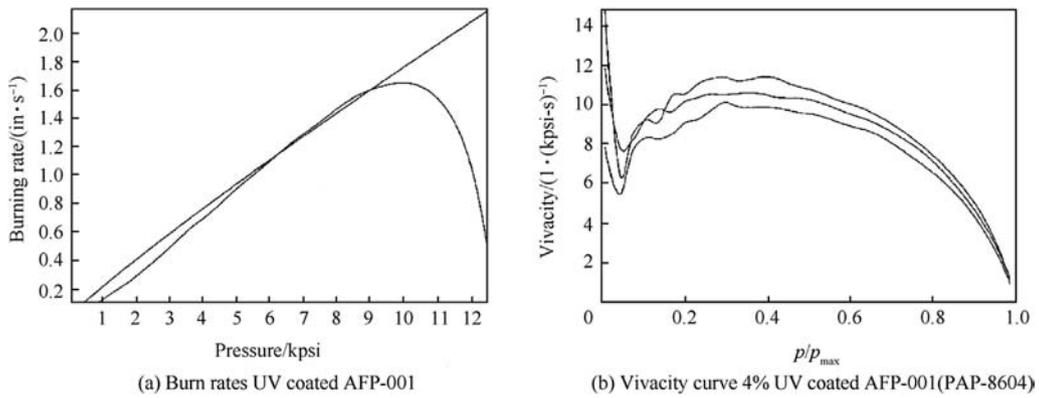


Fig. 20. Burn rates UV coated AFP-001 and vivacity curve 4% UV coated AFP-001(PAP-8604).

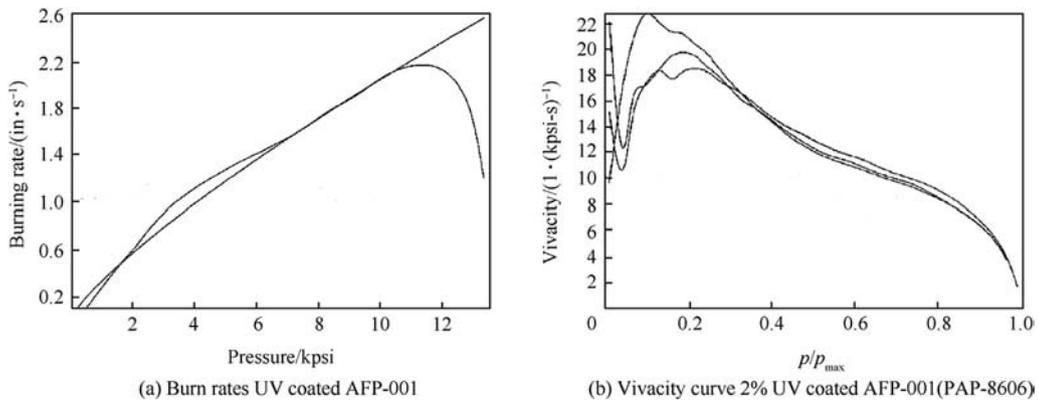


Fig. 21. Burn rates UV coated AFP-001 and vivacity curve 2% UV coated AFP-001(PAP-8606).

Fig. 29 for LED UV Coating Formulation PAP-8604-2 were lower than the uncoated AFP-001 at cold, comparable at ambient and higher at hot temperatures. At ambient temperature, 21 °C, the apparent burn rates and the vivacity curves of surface coated with LED UV coating formulation PAP-8606-4 and 8604-4 were higher than the uncoated AFP-001 shown in Figs. 25 and 26, the same behavior were observed for the muzzle velocities and breech pressures when shot.

4. Summary and conclusions

The effects of photo-initiators and reactive diluents on the

wettability of various LED UV coating formulations were demonstrated. The effects of the droplet size diameter for the LED UV coating formulations were larger when compared to the other LED UV coating formulations investigated. A larger droplet diameter represents spread-ability of the LED UV coating on the surface of the substrates. The first proof of the phenomena is that the LED UV coating formulations 8606-4 and 8606-2 apparent burn rates were higher compared to the other LED UV coating formulations shown in Fig. 25. The second proof of the phenomena is that the LED UV coating formulations 8606-4 and 8606-2 have a much higher vivacity curve which is an indication of more oxygen in the LED UV coating formulation compared to the other LED UV coating

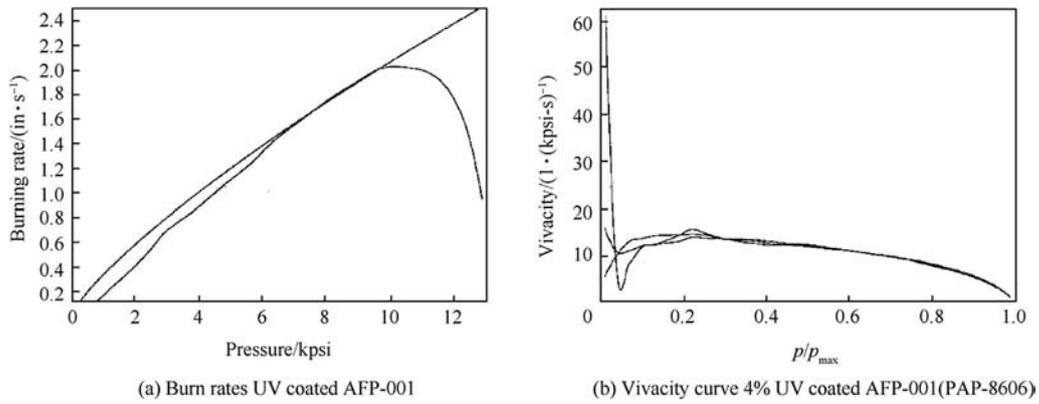


Fig. 22. Burn rates UV coated AFP-001 and vivacity curve 4% UV coated AFP-001(PAP-8606).

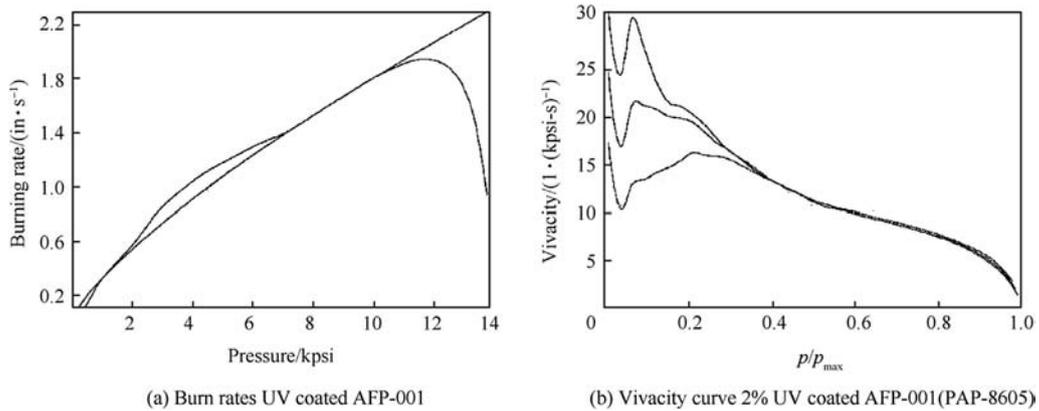


Fig. 23. Burn rates UV coated AFP-001 and vivacity curve 2% UV coated AFP-001(PAP-8605).

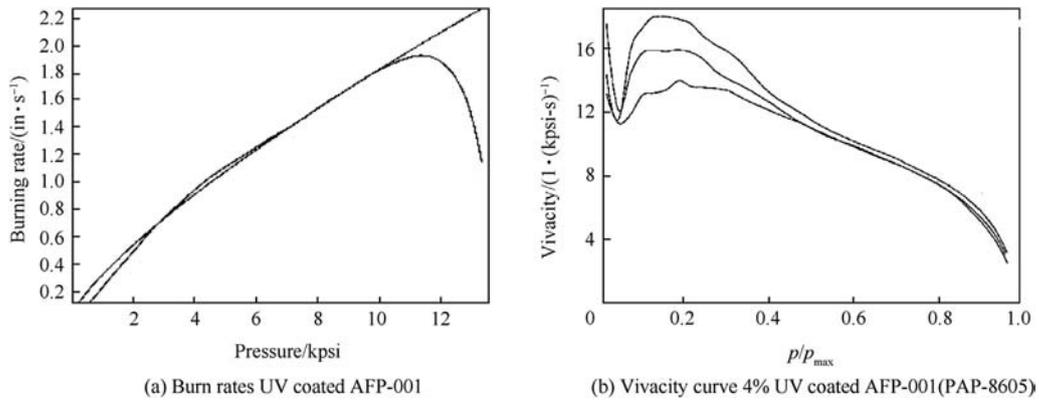


Fig. 24. Burn rates UV coated AFP-001 and vivacity curve 4% UV coated AFP-001(PAP-8605).

**Table 9**  
Burn rate pressure exponent, pressure coefficient, and pressure at uniform range.

UV coating formulation	Pressure coefficient $\alpha$	Pressure exponent $\beta$	Uniform range/kpsi	Uniform range/%
AFP-001	0.174745E-02	0.751744	6.7–11.8	46.9–82.6
8604–2	0.117239E-02	0.796853	5.7–10.5	41.8–77.0
8604–4	0.374796E-02	0.917570	5.3–9.8	41.8–77.3
8605–2	0.160165E-02	0.763134	7.1–10.3	50.9–73.8
8605–4	0.145120E-02	0.774627	7.1–10.1	51.7–73.5
8606–2	0.127322E-02	0.801556	7.1–10.2	52.0–76.8
8606–4	0.146678E-02	0.785863	6.9–10.0	52.2–76.4

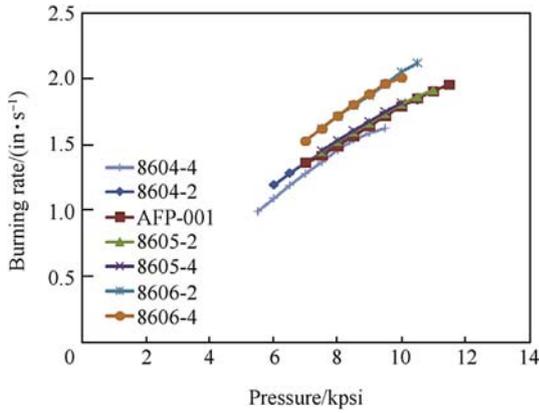


Fig. 25. LED UV coated and Un-coated AFP-001 Apparent Linear Burn Rate at Linear Range.

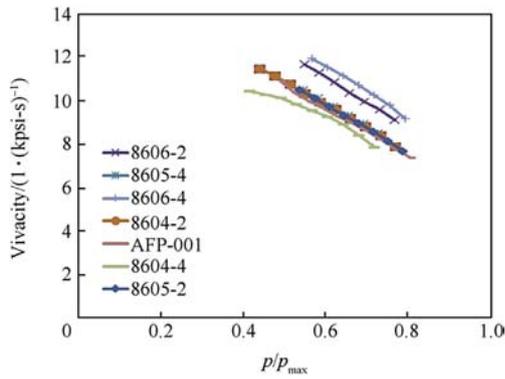


Fig. 26. LED UV coated and Un-coated AFP-001 Vivacity Curve at Linear Range.

formulations shown in Fig. 26. In addition, the  $T_g$  for PAP-8606 LED UV coating formulation was  $-31.52\text{ }^\circ\text{C}$ . During the propellant

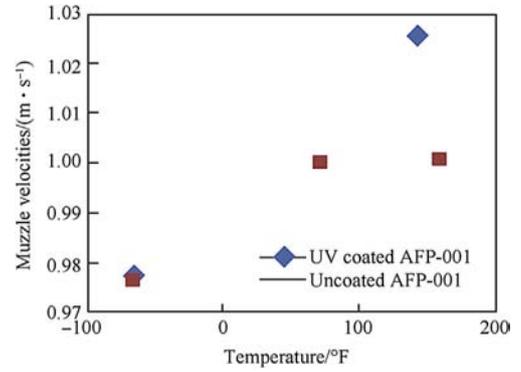


Fig. 28. Muzzle Velocities for Uncoated and LED UV Coating Formulation PAP-8604-2 in 30 mm Sub-scale Gun.

burning, the LED surface coating formulation PAP-8606 was breaking up exposing more surface area in so much controlled way exposing more propellant surface. This phenomena gives an increase in the apparent burn rate and vivacity resulting in progressivity. The LED UV coating formulation PAP-8606 do not contain any of the two reactive diluents, SR 256(SR256, 2 (2-Ethoxyethoxy) Ethyl Acrylate) and SR 506A. The vivacity curve shown in Fig. 26 indicates that the mass rate of combustion or the rate of gas generation is higher for LED UV coating formulation 8606-4 and 8606-2, and followed by in decreasing order 8604-2, 8605-2, AFP-001, and 8604-4. For the first iteration 30 mm sub-scale gun firing ( $30 \times 173\text{ mm}$ ), the LED UV coating formulation PAP-8604-2 was selected for the initial proof of concept. A final blend configuration was chosen for a final set of ballistic tests. The final AFP-001 propellant blend was an uncoated and LED UV coated blend. Final ballistic results are shown in Fig. 27. The muzzle velocities of AFP-001 surface coated with LED UV coating formulation PAP-8604-2 were comparable to the uncoated AFP-001 as shown in Fig. 28 except at hot temperatures. The muzzle velocity of LED UV coating formulation PAP-8604-2 at hot temperatures was higher

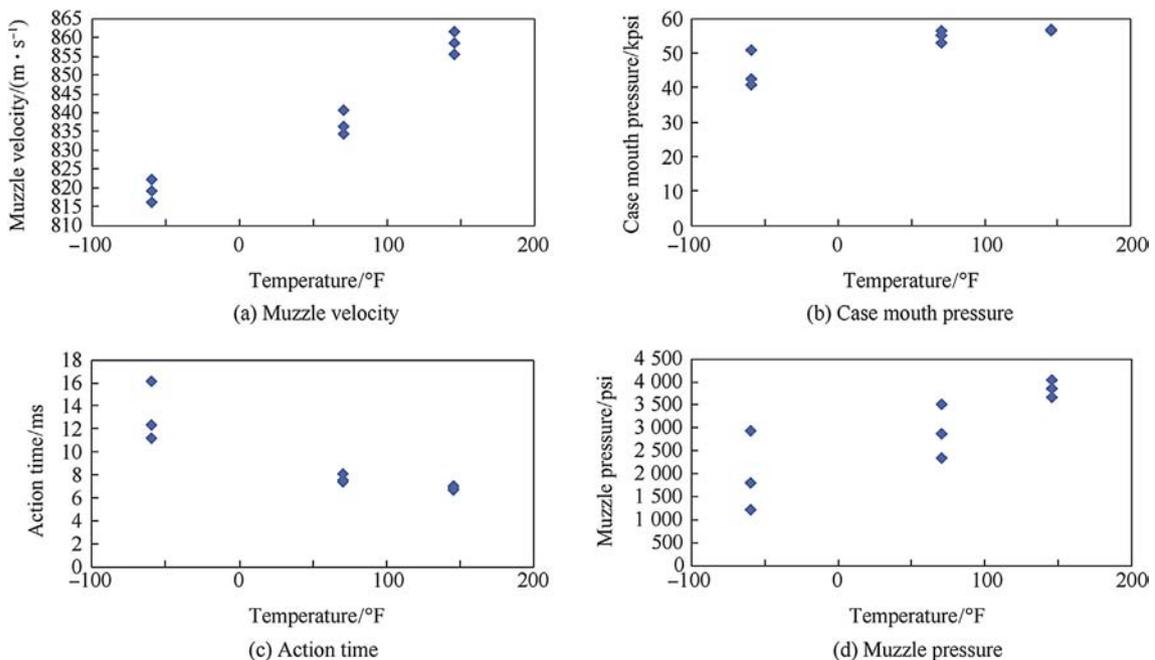


Fig. 27. Summary of Ballistic Data from the 30 mm Gun Firing of LED UV Coating Formulation PAP-8604-2 in 30 mm Sub-scale Gun.

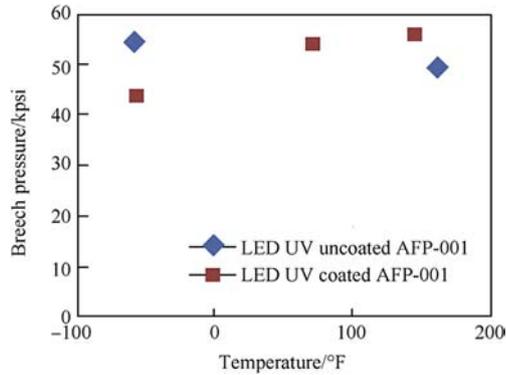


Fig. 29. Breech Pressures for Uncoated and LED UV Coating Formulation PAP-8604-2 in 30 mm Sub-scale Gun.

than the uncoated AFP-001. The Breech Pressures for LED UV Coating Formulation PAP-8604-2 were lower than the uncoated AFP-001 at cold, comparable at ambient and higher at hot temperatures. At ambient temperature, 21 °C, the apparent burn rates and the vivacity curves of surface coated with LED UV coating formulation PAP-8606-4 and 8604-4 were higher than the uncoated AFP-001 shown in Figs. 25 and 26, the same behavior were observed for the muzzle velocities and breech pressures when shot.

#### Future work

The LED UV coating formulations will need a second iteration

formulation modification and further characterization. Additional 30 mm × 173 mm sub-scale gun firings are necessary for all the three LED UV coating formulations candidates listed in Table 8 to be able to verify if the goals and objectives previously discussed are met.

#### Acknowledgments

The authors would like to acknowledge the FREEDOM Tech Base Program and the US Army RDECOM ARDEC for their support and the funding provided for this effort.

#### References

- [1] Adam C, Rozumov R, Grau H. Investigation of the effects of dibutyl phthalate migration in propellant grains on the ballistic performance of small caliber weapons, 60th JPM/9th modeling and simulation/7th liquid propulsion/6th spacecraft propulsion joint subcommittee meeting joint Army-Navy-NASA-air Force (JANNAF). Cheyenne Mountain Conference Center. 29 April-2 May, 2013.
- [2] Fry RS, Peters ST. Burning rates of standard solid propellants for gun applications. Columbia, MD: CPTR 99-69, CPIA/JHU; Sep 1999.
- [3] Irie M, Iga R. *Macromolecules* 1986;19:2480.
- [4] Machalka, E. Dipl.-Ing, AVL Prof. List Ges.m.b.H., Programs for the Determination of Propellant Characteristics in Conjunction with Closed Vessels. Special Edition of Proceedings, 3rd International Symposium on Ballistics 02.
- [5] Drobný JG. *Radiation technology for polymers*. 2nd ed. CRC Press; 2010.
- [6] Ravve A. *Light associated reactions of synthetic polymers*. Springer Science; 2006.
- [7] Klingaman KW, Domen JK. The role of vivacity in closed vessel analysis [JANNAF Propellant Development and Characterization Subcommittee Meeting, Patrick AFB, FL]. 1994.