Composite Color Stars

Scot Anderson
13528 Elsie Road, Conifer, CO 80433, USA

ABSTRACT

Ammonium perchlorate has long been used to produce high-quality color stars and lances. In this article the author uses the basic ingredients of composite rocket propellants to generate colored flame suitable for pyrotechnic display. The use of composite materials has several advantages over classic formulations in that the material is handled in a semi-liquid state prior to cross-linking, produces little smoke, exhibits vibrant color, and uses no water in the manufacturing process. Several formulations are discussed along with visual observations from ground burn and star gun tests.

Keywords: composite rocket propellant, ammonium perchlorate, color stars, hydroxy terminated polybutadiene, HTPB, chromaticity, prime, formulation

Introduction

Ammonium perchlorate has long been used as the principal oxidizer in solid composite rocket motor propellants. A tremendous amount of research by both commercial and military laboratories is available regarding the burning characteristics of these composite materials.[1–3] Ammonium perchlorate has also found some use in pyrotechnics because of its excellent color production and low smoke output.[4,5] The author's interest in composite rocket motor propellants initiated the research outlined in this paper.

Generally speaking, rocket motor propellants have different formulations and requirements than pyrotechnic mixtures. Characteristics such as burn rate, energy content, geometric configuration, and even opacity are usually carefully controlled to produce the desired ballistic performance in a given rocket motor design. Copper chromite ($Cu_2Cr_2O_4$) has been used as a burn rate modifier in ammonium perchlorate composite rocket motors.[1,2] Copper chromite is both expensive and difficult to procure so copper(II) oxide was used in its place. As it turned out, copper(II) oxide performed as a satisfactory burn rate modifier for the author's rocket motor research and had the unexpected benefit of giving the flame a magenta coloration. It should be noted that copper(II) oxide and copper metal act as catalysts for hydroxy terminated polybutadiene (HTPB) further cross-linking the resin, thereby causing a loss of elasticity in the finished product over time. This would be a concern for the long term storage of rocket motor grains but should cause little trouble with fireworks stars.[6] The magenta formulation used during this test was not applicable to this paper, but the coloration was produced by 0.1 weight percent of copper(II) oxide! This concentration is ridiculously low when compared with most pyrotechnic color compositions. Many contain 10% or more copper(II) oxide to produce a satisfactory blue; older formulations sometimes called for nearly 20% Paris green ($Cu(C_2H_3O_2)_2 \cdot 3Cu(AsO_2)_2$)* to generate rather poor blues.[4,7]

Why investigate new color formulations? Composite materials have several properties that typical color star formulations lack. In particular, the material is handled in its semi-liquid state, allowing new, perhaps safer, manufacturing processes, such as extrusion and casting. The process involves no water or other ionic solvent. This eliminates one of the common dangers of fireworks manufacture, ion exchange during processing and drying. Further, the cured product is relatively safe, waterproof, and not prone to accidental ignition. Indeed successful ignition in a shell burst is one of the difficulties

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* This formula is from the *Handbook of Chemistry and Physics,* 61st ed. CRC Press 1980–1981.

encountered with composite stars. The finished product produces a voluminous, almost transparent flame from very tiny stars. These stars do not dry but cure by cross-linking in 24 hours and do not require heat or evaporative cooling to cure. Finally, the colors produced with these formulations are among the best the author has seen. Indeed, many people have indicated that the red, orange and green formulations are as pure as any ever witnessed. This observation has been borne out with chromaticity and spectral testing.[8,9] It has been noted that the burning characteristics of polybutadiene closely resembles that of shellac, perhaps even surpassing it, in flame clarity. Many readers will no doubt envision formulations the author has not tried or conceived.

Colored flames are generally produced by the spectral emission bands of metal monochlorides excited by the high temperature flame developed from the combustion of a fuel with an oxidizer. In many color star formulations, chlorinated fuels such as polyvinyl chloride (PVC), Parlon®, or Saran® resin are added to ensure a sufficient quantity of chlorine to form the desired metal monochlorides. The metals in most common use are strontium, sodium, barium, and copper. Occasionally other metals such as zinc and calcium have been used. The oxidizer, ammonium perchlorate, has an abundance of chlorine that becomes available during the decomposition of the oxidizer. This, no doubt, is a primary reason that the color star compositions researched in this work produce such exemplary colors. In addition, ammonium perchlorate decomposes to all gaseous products, reducing solid particle incandescence.

When this work was initiated, only a few questions were really considered. Would composite materials lend themselves to fireworks? Could colors suitable for display fireworks be obtained from these compositions? Could composite color stars compete with the state of the art found in modern color star formulations? As this research has continued, these simple questions have been answered in the affirmative. Of course, this has lead to the asking of many more questions. Hopefully, this paper outlines the journey of discovery and will spur yet more research into this fascinating subject.

Cautionary Notes

The resin used for this work was R45 hydroxy terminated polybutadiene (HTPB). The resin is very sticky and has a characteristic odor. Care should be taken to provide adequate ventilation. The effects of prolonged breathing of vapors are not listed as harmful in the Material Safety Data Sheet (MSDS) but reasonable care should be exercised in any case. The author always used disposable gloves when handling resin components and was careful to avoid skin contact.

All catalysts and hardeners should be treated with the respect due any active chemical. Diphenyl methane diisocyanate (MDI) was used as the curative for these experiments. It has been suggested that this material is hazardous and should be kept in a safe place and used in small quantities. The MSDS indicates that the vapors should not be inhaled nor should the material be allowed to come into contact with the skin. The MSDS also indicates that the material is a strong irritant to skin and mucous membranes as well as being a sensitizer. MDI decomposes spontaneously in the presence of water or excessive heat; so care should be taken to keep it dry and between 50 and 95 °F. It has also been suggested, and the author concurs, that other, low vapor pressure, cross-linking agents such as diisopherone diisocyanate be tried to avoid some of the potential risks associated with MDI.[6]

Dioctyl adipate (DOA) was used as a plasticizer. DOA is used in vinyl tubing, Saran® resins, and PVC sheeting. The MSDS lists only irritation to the skin and mucous membranes as the immediate health dangers associated with DOA. Long term effects are less clearly known, but there is evidence that DOA is a carcinogen. Personal protective equipment should be worn, and the material should be handled in areas with plenty of ventilation. DOA is a strong plasticizer, however, and tends to soften or dissolve vinyl gloves and utensils; so care should be exercised in selection of protective equipment and materials.

Salts used as color agents pose their own risks, especially soluble barium compounds. Care should be taken to avoid breathing the dust from these chemicals. Barium perchlorate is also a strong desiccant and will cause a chemical burn to unprotected skin and eyes. Because the color agents are typically fine powders, they pose an additional inhalation risk. Dust filter respirators should be used by persons using these chemicals. The author used a high quality nose and mouth dust mask with replaceable filter cartridges and full eye protection when working with these chemicals.

The mixed resin-oxidizer system will burn vigorously in the uncured state. While this makes testing of new formulations easy, it poses some danger during manufacture. As always, care should be taken to avoid sources of ignition during mixing and curing. When the mixed product is burned, either in the cured or uncured state, copious quantities of hydrogen chloride gas are released. DO NOT breathe the smoke from burning composites or ignite them in a confined area. While this prevents using these compositions indoors, composite formulations are burned in hobby solid propellant rocket motors frequently, so their use in outdoor fireworks poses few risks except downwind. One final note, the burning material is often propulsive and can easily skitter across a flat surface. As with all pyrotechnics, care should be taken to remove other combustibles from the testing area.

Fuel and Oxidizer

The oxidizer used for these tests was solid propellant grade ammonium perchlorate from either Kosanke Services[10] or Pacific Engineering[11]. The oxidizer was purchased as rotary-rounded, 200-micron spheroids. Experiments on mixing have shown that fine powder is very hard to mix into the final composition. The nascent fuel-oxidizer mix (sans color agent) contains 85% by weight ammonium perchlorate and 15% by weight HTPB. The maximum volume that can be filled with perfect spheres is 64% for the cubic arrangement and 74% for hexagonal close pack. The density of ammonium perchlorate is 1.95 g/cc, and the density of the uncured HTPB is 0.9 g/cc; thus under ideal conditions, the mixture should contain few voids. However, because of the hand mixing and the lack of vacuum degassing, the mixture discussed in this work contains significant voids. While this would prove disastrous for solid rocket propellant, it is quite acceptable for color star compositions.

The fuel used was hydroxy-terminated-polybutadiene (HTPB), R45 from Sartomer Corp.[12] This resin is a clear viscous fluid and has a strong characteristic odor. A syringe was employed to dispense the resin, and acetone was used for cleaning the uncured resin from mixing bowls and utensils.

The dioctyl adipate used was purchased from BASF[13] under the trade name Palatinol®. DOA was added to the resin as a plasticizer to facilitate hand mixing with the oxidizer. It readily dissolves PVC's and some polyurethanes; thus polyethylene, nylon, or stainless utensils are needed.

The cross-linking agent used was diphenylmethane diisocyanate (MDI) from Dow Chemical.[14] MDI is a clear yellow liquid with no detectable odor. It should be stored under controlled temperature conditions; however, the author's supply has not been maintained under temperature control, is several years old, and still works well.

Table 1 lists the fuel mixture by component. The weights listed provide sufficient fuel for two 100 gram batches of mixed composition. As a practical matter the colorants were typically added to the mixed fuel prior to adding the oxidizer. Once mixed, the fuel has a useful pot life of about 2 hours, though at the end of this time it is noticeably more viscous. During the cure process, the fuel is sensitive to atmospheric water, and a foam will form in high humidity regions. This work was done where relative humidity seldom exceeds 20%; so this was not a concern. The weight percent of the ingredients listed in Table 1 were determined empirically and are not meant to be taken as stoichiometric or optimized quantities.

Table 1. Base Fuel Mixture for Composite Color Stars.

Ingredient	Weight (g) *	Weight %
HTPB	24	80
MDI	2.9	9.7
DOA	3.1	10.3
Total	30	100

* Weight for 200 grams of mixed composition.

To mix 100 grams of composition, the above fuel was divided into two 15-gram batches. The desired color agent was added to the liquid resin and thoroughly mixed. This resin mixture was then added to 85 grams of ammonium perchlorate to make about 100 grams of mixed fuel-oxidizer-colorant. Mixing was performed in a bowl by hand; no mechanical mixing was employed. The mixed propellant formed a soft dough, similar to cookie dough. Once well mixed, the composition can be processed in a number of ways to make stars. This includes flattening to make cut stars, pumping and extruding to make pumped stars, or even molding into round or other shapes. The author commonly pumped the dough into a 1/4" tube and pressed it out with a wooden dowel, forming 3" long cylinders. Curing was performed on waxed paper sheets at 25 ºC and took about 24 hours to complete. When cured, the composition was tough and flexible, resembling an art-gum eraser, and could be easily cut or broken into appropriate sized stars, star cores, or lances. No special drying screens or equipment were required.

A System of Colors

As this research progressed, it was realized that the colors produced with this system were exceptional. This being so, it became a goal to produce a system of colors that could be mixed to produce virtually any color. Thus, the ultimate goal was to produce an additive color system whereby the shell maker could pick a set of color coordinates, convert this to colorant amounts, mix a standard batch of composition, and produce stars of the desired color. This process was envisioned to be much like commercial paint mixing, and would provide easily reproducible designer colors. Such systems are not new and have been proposed and compounded by others.[5,14–16] The final formulations are listed in Table 4.

Figure 1 shows the standard CIE Chromaticity Diagram for the human eye.[18–21] Note that the author used the 1964 CIE supplemental standard observer because it was determined using 10 degree field of view. The 1931 CIE standard observer used a 2 degree field of view. In the author's opinion, the wider field of view is more likely to represent a spectator's perception of the entire shell; it may not represent the color perceived from a single star in the central visual field. The black dots are the approximate location for the Red, Orange, Green, Blue and Purple starting with the red corner and progressing counterclockwise. As may be seen, the red and orange are essentially pure colors. The green is not fully pure. The blue is more cyan and is also not pure. During a weekend investigation of color stars, Clive Jennings-White provided a Minolta XY-1 chromaticity meter. Data presented in Figure 1 were taken using this instrument and show the quality of color, especially for the red and orange. These data indicate that the colors produced by these formulations have the highest purity seen for red, orange, and green.[8] A handheld Zeiss spectroscope and several spectrometers were also used to make a detailed qualitative analysis of the burning composition. The outcome of this analysis will be presented with the full discussion of the colors.[9] The dark lines between the chromaticity coordinates represent the gamut of colors that may be obtained using the composite formulations described here. As is clearly

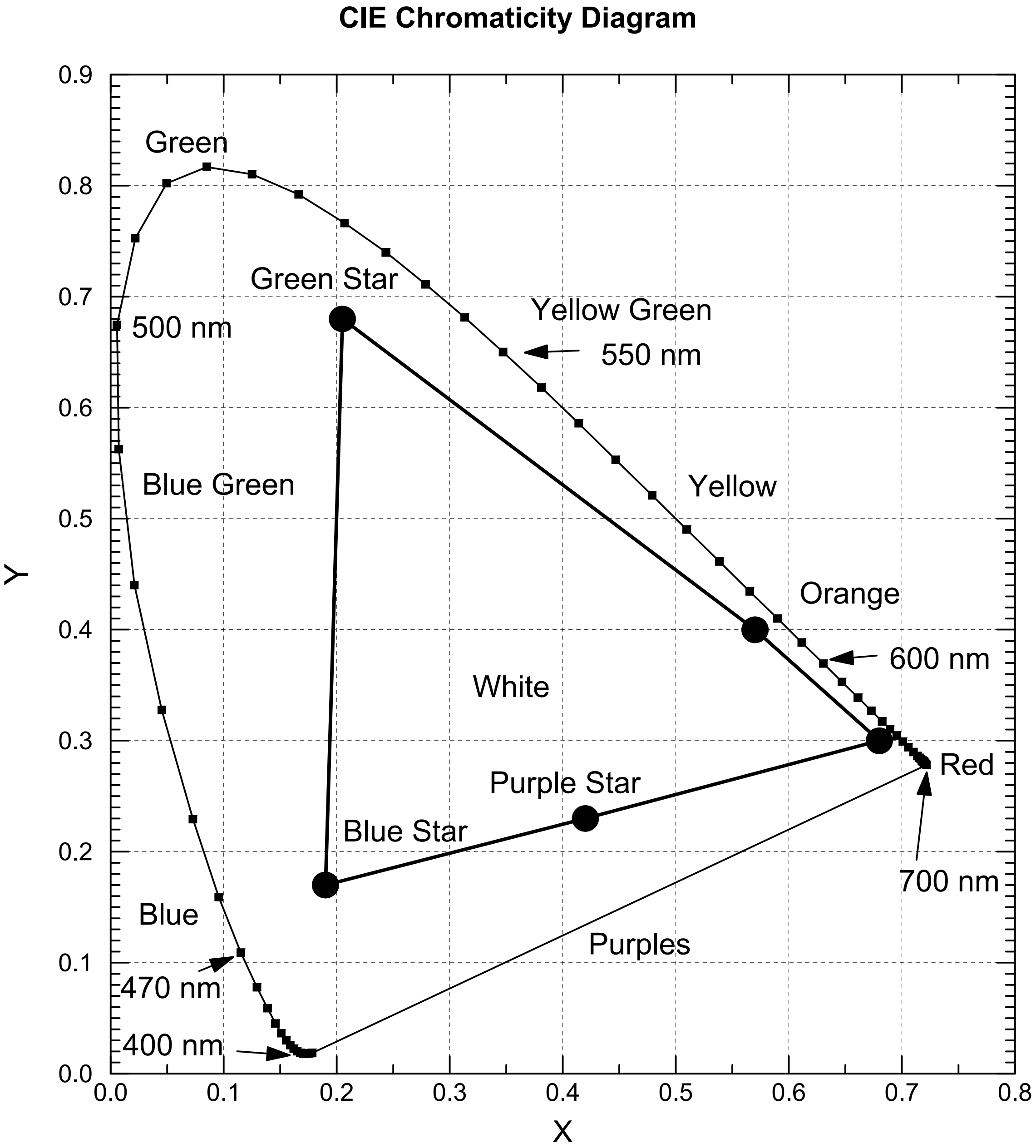

Figure 1. CIE Chromaticity diagram (1964 data) showing the color gamut for composite color stars.[21]

shown, the lack of purity in the blue and green limit the quality of colors that may be obtained by a simple mixture of the two. Deeply saturated blue green is not possible at this time. Work is continuing on this subject and will be presented in a future paper.

Red

Strontium carbonate or strontium nitrate was used to produce red. Both compounds produced a very deep, saturated red when added as an additional 5% (e.g., 5 grams added to a 100 gram batch of neutral composition). The flame had a striking translucent quality, producing an outstanding red. Strontium, in either form, appears to be a burn rate catalyst, accelerating the burn rate above that of the neutral mixture. The fast burn rate of this composition makes it suitable for aerial shells and display set pieces. As shown in the chromaticity diagram, the flame is essentially pure; so no further improvement in color is needed. Further, the eye is not very sensitive to spectral shifts at these wavelengths; so a deeper red seems unlikely at this time.

Spectrographic analysis of the flame showed an abundance of red spectral bands. These are most likely caused by the presence of strontium monochloride in the flame, but the spectroscope used had insufficient resolution to determine this absolutely. To the eye, there was very little difference in color between the longest and shortest of these spectral bands. No serious black body continuous spectra were evident in the flame, which explains the observed translucent quality. There was evidence of both calcium and sodium lines in the flame. The source of these lines is detailed in the discussion of green as they cause no difficulty with the red.[9]

Orange

Calcium sulfate (anhydrous), as an additional 5%, produced a very pure orange red. The flame had similar characteristics to that of strontium, except that the burn rate does not appear accelerated. The flame was also more opaque, possibly indicating the presence of incandescence. The color produced is most unusual but is not really orange. A quick look at the chromaticity diagram indicates that, for a better orange, the color must be shifted toward the yellow.

Shifting toward the yellow could be done with either sodium or barium. After several experiments, barium was found to produce an exceptional orange flame. Spectroscopic analysis revealed the presence of both calcium and barium monochloride; as expected, it also revealed sodium. The chromaticity meter showed a fully saturated color. As with red, further work with this color is not going to yield major improvements. One note, the sodium tended to be a strong color agent, and it produced similar shifts to the yellow at lower concentrations, thus with less fidelity than barium.

Yellow

Sodium chloride produces the strong, characteristic color of sodium. Color saturation is very high, almost monochromatic. Again, the flame has the transparent quality characteristic of this color system. Since sodium yellow is really slightly red, the addition of barium could be used to shift the color to a more pleasing canary yellow color. No spectral analysis of these colors has yet been performed.

Green

The addition of 5% barium nitrate to the neutral composite star mixture produced a yellow flame of low purity. Even when this amount was doubled to 10%, the color was neither pure nor aesthetically pleasing. Although spectroscopic analysis of these colors has not been performed, the author suspects incandescence and contamination to be the primary faults. The difficulty with green was solved after many debates and consultations.

Historically, the best green colors were produced using barium chlorate.[4] Aside from the sensitive nature of barium chlorate, mixing it with ammonium perchlorate could be highly dangerous.* However, a close examination of several, so-called, exhibition green formulations showed an extraordinarily high concentration of barium salts. For example, Weingart's exhibition green calls for almost 90% barium chlorate and 10% shellac.[7] At first, it was hypothesized that the high molecular weight of barium might be reducing the ion concentration in the flame thus reducing the number of emission sources. An analysis of atomic concentration for barium compared to strontium and calcium showed that if low ion concentration was the cause, the 10% formulation should have worked. It did not.

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* A double-base decomposition reaction could form explosive ammonium chlorate, even in the non-aqueous bound stars discussed in this article. The effect of even microscopic concentrations of ammonium chlorate on these compositions is unknown and considered too dangerous to study. In any case, formulations utilizing chlorates and perchlorates would not be suitable for display fireworks.

The first requirement, however, was to get a good green formula. Charley Wilson suggested that the barium nitrate be increased to 35% based on Lancaster's green fire 'B', substituting HTPB for the red gum.[4] Wilson showed that this formulation produced a good green using shellac instead of red gum. To compensate for the added oxidizer the amount of ammonium perchlorate was reduced. Table 2 shows this green formulation.

Table 2. Exceptional Green Color Formulation.

Ingredient	Weight (g)
Ammonium perchlorate	50
Barium nitrate	35
Mixed resin	15
Total	100

This green was of high quality, certainly as good as the barium chlorate green of old. However, chromaticity analysis showed that while this green was the purest green having yet been measured, it could be improved. The spectroscope still showed the annoying calcium and sodium lines evident in the other colors. It was suspected that the presence of the contamination was causing the green color to be shifted to the whiter region of the chromaticity diagram. Since calcium and barium are chemically very similar, it seemed likely that the calcium was a natural contaminant of the barium nitrate. Sodium was ubiquitous; so its source could be anywhere. Spectroscopic analysis of the component chemicals revealed, surprisingly, that the ammonium perchlorate was contaminated with both sodium and calcium. Some research showed that this might not be so odd since ammonium perchlorate is produced by the electrolysis of aqueous sodium chloride. The calcium may be present as a trace element in the water used during processing.

While the barium nitrate produced an excellent green, it burned very slowly. Simulated wind tests and star gun tests showed that the finished product would not stay lit in high speed air. Indeed, throwing a lit star would sometimes extinguish it.[15,16] Various schemes were tried to improve the burning speed of the barium nitrate based green, some of which have not been fully explored. The final formulation given in Table 3 was developed by Charley Wilson and used anhydrous barium perchlorate.[15]

Normally anhydrous barium perchlorate would not be used in fireworks because it is very hygroscopic. The non-aqueous composite binder coupled with the fact that the stars are essentially encased in rubber after curing, allowed its use here. These stars burned very quickly and produced an exceptional green. Stars using barium perchlorate have been stored in an open container for several weeks with no apparent loss of color or the appearance of pools of liquid even at cut edges.

Table 3. Green Formulation.

Compound	Weight (g)
Ammonium perchlorate	45
Barium perchlorate	40
Mixed resin	15
Total	100

The lack of purity was still troubling, however, not so much that the color was poor, but because as a part of a color system, it excluded the color palette on the blue-green side of the chromaticity diagram.

During the course of this investigation a formulation of 85% barium perchlorate and 15% HTPB was tried. This high barium concentration produced a less vivid green with an abundance of smoke. Some of the lack of saturation is certainly due to incandescent barium byproducts in the flame. The low concentration of metal salts in the other colors might keep the incandescence at a low enough level that it does not significantly affect the resultant color. Barium green colors may also be more sensitive to impurities in the constituent salts. This hypothesis will be tested in future research using high purity chemicals. Further, as shown in Figure 1, the chromaticity diagram indicates that the eye is exquisitely sensitive to very small shifts in wavelength and saturation level at green wavelengths.* The problem may simply be that the high concentration of barium metal in the flame limits saturation by incandescence, compounded by the human eye being more sensitive at these wavelengths.

Blue

Copper(II) oxide, used as a burn rate modifier, initially started this whole investigation by producing a colored flame. Close examination of stationary burning blue composite stars showed red flame tips. This was true of most, if not all, blue formulations. Some investigators have indicated that the addition of certain nonhydrocarbon fuels reduces the effect of red flame tips on blue colors.[15] Since the basic research involves HTPB, the elimination of hydrocarbons was not considered. Other than the tips, the flame was quite blue and was one of the better ones the author has seen.

The chromaticity meter, however, indicated a less than pure cyan. The loss of purity might be explained by the red from the flame tips. It required spectroscopic analysis to get to the bottom of the cyan color. The spectroscope revealed a plethora of blue bands, just what one would expect from copper monochloride; but it also indicated strong green bands. The source of the green was not known, but copper hydroxide or copper oxide was strongly suspected. The presence of green shifted the blue to a region of the chromaticity diagram where the eye is, again, very sensitive to wavelength variations. Clearly to deepen the blue, the green band intensities should be reduced.

How to reduce the green intensities is unknown and will be the subject of future research. One of the first attempts will be to try anhydrous copper(II) perchlorate. Copper perchlorate is strongly deliquescent; so it is not usually considered for pyrotechnic mixtures. This system, however, does allow the use of more hygroscopic materials such as barium perchlorate. Purifying the blue, in the color system, would also enhance the quality of color available on the blue green side of the spectrum.

The author notes that most blue and green formulations are not pure, and this may explain the lack of good aqua colors. Zinc has been used to fill this gap but has not been tried in this color system. A quick look at Pearse and Gaydon[22] indicated that zinc chlorides do not emit in the blue or green.

In the author's experience, blue is a very difficult color to produce. Some compositions that perform well in a static test near the observer do not perform nearly as well at a distance while moving. Similarly, good blues in aerial displays sometimes appear weak when burned on the ground. Air temperature, as well as, flame temperature also appears to have strong effects on the quality of blue stars. Star gun testing has shown this composite blue can hold its own against others, but the real test will be how it performs in a shell and that has not yet been tested.

Purple

Violet and purple are not spectral colors and must be produced by the combination of red and blue. As expected, the purples that can be produced fall on the line between the blue and red coordinates in Figure 1. The purple is quite good and can be dialed in as desired. One should note the very low concentration of color agents and the low concentration of copper(II) oxide (2%). The chromaticity diagram explains why. The line between the blue and red passes near white. As more strontium is added to a blue flame composition, the color first moves toward white and becomes pinkish; it then passes into more pure purple colors yielding a deep satisfying color. It is a strong statement that the blue emission bands can compete satisfactorily with red at these low concentrations.

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* The small squares on the chromaticity diagram in Figure 1 are spaced at 5 nm intervals. The closeness of sequential points at red and blue indicate that the eye is less sensitive to spectral shifts at these wavelengths. Green (540 nm), however, has the squares spaced far apart indicating high spectral resolution by the eye. The human eye is most sensitive at green wavelengths and is capable of discerning small changes in purity. This is indicated by the relatively large distance between white and the spectrally pure greens. For more information see references 18–20.

Prime

Historically, an outer coating of a material that easily takes fire and then transfers fire to the actual star composition is called prime. Most fireworks stars are primed to improve ignition efficiency during the violent shell burst. Composite star formulations, like their progenitor propellants, are notoriously difficult to ignite. Research into priming compositions and methods showed that strobe stars are also difficult to ignite and pointed the way to successful priming of the composite stars.

The poor ignition properties of composite materials are due, in part, to the higher activation energies of the constituent components. It is also, in large part, due to the inhibition caused by the rubber coating on the ammonium perchlorate spheroids in the cured composition. Finally, the rubber coating on the star may not take a water-based prime effectively, increasing the difficulty of finding a workable prime formulation. Water-based primes may also produce undesirable double-base decomposition reactions between the ammonium perchlorate and the other salts used in the star composition or the prime itself; thereby, significantly altering the performance of the finished star.

A suitable prime was found in Takeo Shimizu's seminal article on strobe stars.[23] Primed stars prepared by Charley Wilson showed 100% ignition when primed with Shimizu's "First Ignition Composition". The prime was prepared with 10% nitrocellulose and thinned to a slurry with acetone. The composite stars were then dipped into the slurry and allowed to dry.

Conclusions

Composite color stars are not only feasible but produce some of the purest colors available to the pyrotechnician. The semi-liquid state of the formulations allows novel processing techniques that may lead to safer, more automated manufacture. The stars produced during this research, 1/4" diameter extruded stars, burned long enough to be useful in 3" and possibly 4" shells. Thus the vibrant color could be combined with dense star patterns. The highly propulsive nature of these stars also lends them to shell special effects such as go-getter, hummer, stickless rocket, serpent, etc. The formulations discussed in this article are presented in Table 4.

Research will continue on the green formulation to improve the color purity and enhance the color gamut available. Further research is

Table 4. Composite Color Star Formulations. (These formulations are based on adding an additional 5% of coloring agent to the standard 85% ammonium perchlorate, 15% HTPB propellant.)

	Color	Colorant 1	Wt %	Colorant 2	Wt %	Comments
1	Red	$SrCO_3$	5	—	—	Outstanding red, transparent flame, slightly propulsive
2	Red	$Sr(NO_3)_2$	5	—	—	Outstanding red, transparent flame, slightly propulsive
3	Red-Orange	$CaSO_4$	5	—	—	Unusual red-orange, transparent flame
4	Orange	$CaSO_4$	2.5	$Ba(NO_3)_2$	7.5	Outstanding color, pumpkin orange, transparent flame
5	Green	*	*			Very good green, as good as barium chlorate
6	Blue	CuO	5	—	—	Good color, slightly cyan, propulsive
7	Purple	CuO	2	$SrCO_3$	3	Good color, transparent flame, propulsive

* Formulation is found in Table 3.

indicated to improve the blue compositions as well. Many new pyrotechnic ingredients are possible with these formulations as evidenced by the barium perchlorate green.

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