

# ENVIRONMENTALLY BENIGN BATTLEFIELD EFFECTS BLACK SMOKE SIMULATOR

Gary Chen, Shawna Showalter, Gretel Raibeck\*, James Wejsa  
U.S. ARMY RDECOM-ARDEC  
Picatinny, NJ 07806-5000

## ABSTRACT

The Pyrotechnic Research and Technology Branch of Armament Research, Development, and Engineering Center (ARDEC) is developing an environmentally benign black smoke composition for use in the Battlefield Effects Simulator. The black smoke simulator meets the outstanding requirements for use in battlefield training applications. A black smoke formulation candidate (Figure 1) has been proven in the laboratory and is currently under system demonstration at the production level.



Figure 1: Smoke image of successful formulation

## 1. INTRODUCTION

The effort of designing an environmentally benign black smoke simulator is part of the US Army Research, Development and Engineering Command (RDECOM) Ordnance Environmental Program. This program is a Pollution Prevention initiative to ensure that the operational ranges and munitions production facilities remain available and sustainable in support of the transforming future forces initiative. The Pyrotechnics Team at Edgewood Chemical and Biological Center (ECBC) provided technical support to the ARDEC Integrated Product Team (IPT) on this effort. The US Army Center for Health Promotion and Preventive Medicine (CHPPM) is conducting a toxicity and environmental analysis of the black smoke components and combustion products.

## 1.1 Background

The black smoke simulator is an integral part of the battlefield training system to indicate that a target, such as a vehicle, has been killed or successfully disabled. The Army is phasing out the M26 Target Kill Simulator due to the obsolescence of the firing systems, environmental concerns, and the pre-mature ignition safety issue in favor of the Battlefield Effects Simulator (BES) systems. There are two BES systems in use: the MGSS (Force on Force) and the Omega 60 (Force on Target) systems. The BES systems are vital for simulating battlefield realism. They are more tactically oriented and are safer in operations than the earlier systems.

## 1.2 Environmental Concerns

The components naphthalene and potassium perchlorate of the M26 Target Kill Simulator (Table 1) pose potential environmental and health concerns. Naphthalene is a suspect carcinogen and is prohibited from use in several states. Its combustion products, including generated black soot, are health hazards. Potassium perchlorate has been linked to the blocking of iodide from entering the thyroid gland, leading to interference in production of the thyroid hormones. Recently, the Environmental Protection Agency (EPA) has recommended a preliminary clean-up goal of 24.5 parts per billion (ppb) for perchlorate. Many initiatives for eradicating perchlorate from the pyrotechnic munitions systems are also underway. There are also some health concerns with the Laminac / Lupersol binder system which contains the highly toxic materials, methyl ethyl ketone peroxide (MEKP) and styrene monomer.

Table 1: Formulation of the M26 Target Kill Simulator

Component	Weight Percent
Naphthalene	28%
Potassium Perchlorate	62%
Laminac/Lupersol	10%

The Army is currently without a suitable black smoke replacement for the M26 in the new BES systems. Successful implementation of an environmentally benign black smoke composition in the BES systems would

# Report Documentation Page

Form Approved  
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE <b>01 NOV 2006</b>		2. REPORT TYPE <b>N/A</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Environmentally Benign Battlefield Effects Black Smoke Simulator</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. ARMY RDECOM-ARDEC Picatinny, NJ 07806-5000</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADM002075., The original document contains color images.</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>UU</b>	18. NUMBER OF PAGES <b>8</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

provide a complete and effective pre-deployment training for our troops.

### 1.3 Design and Performance Criteria

The requirements for the black smoke simulator are 1) to be integratable into the BES systems hardware; 2) visible smoke for 20-25 seconds; 3) black in color; 4) smoke daytime visibility distance at 1800 meters. While these are the criteria that our research has strived to attain, the requirements are static and may change at the discretion of the user.

## 2. POTENTIAL BLACK SMOKE SYSTEMS

After an extensive literature search on the principles of black smoke generation, several methods were selected for examination based on the criteria that the system munitions components and their combustion products are environmentally benign. Organic fuels that produce black smoke based on the cracking of heavy hydrocarbons, such as anthracene and similar compounds, were not considered. While this method produces the best quantity and quality of black smoke needed for simulation, these materials have the same potential health and environmental hazards as naphthalene. Due to strict EPA regulations and health hazards, oxidizers containing perchlorates or heavy metals or other chemicals considered to be potential toxins or carcinogens were excluded from examination.

### 2.1 Combustion of Sugar or Wax Based Hydrocarbons

The first method assessed was the combustion of hydrocarbons, such as waxes and sugars, with an oxidizer to produce black smoke as in the naphthalene based approach. In principle, the smoke is generated from the soot in the air, which is partially cracked hydrocarbons, as well as carbon particles, carbon dioxide, carbon monoxide and water. However, the several waxes and other organic compounds tested only produced, at best, a thin grey smoke, as summarized in Table 2.

Table 2: List of organic compounds tested and results

Fuel	Oxidizer	Color of Smoke	Density of Smoke
Sugar (Sucrose)	KNO <sub>3</sub>	Grey	Medium
Dextrin	KNO <sub>3</sub>	Grey	Thin
Microcrystalline Wax	KNO <sub>3</sub>	White	Very Thin
Carnuba Wax	KNO <sub>3</sub>	Grey	Very Thin
Camphor	KNO <sub>3</sub>	Grey	Very Thin

### 2.2 Combustion of Fluorocarbon

Another method tested for viability was the combustion of fluorocarbons, such as polytetrafluoroethylene (PTFE) as the oxidizer with powdered aluminum as the fuel. This combination appears often in pyrotechnics as a heat signal producer. By adjusting the ratio of fuel to oxidizer, with a PTFE rich formulation, it was expected to generate black smoke through the formation of suspended carbon particles. Initial tests were only marginally successful. Black soot was generated, but nothing as opaque as to satisfy the simulation of smoke. Also, recent EPA initiatives have stated that PTFE may have serious health concerns related to perfluorooctanoic acid (PFOA).

### 2.3 Physical Dispersion of Fine Carbon Particles

A physical dispersion method using fine black carbon particles has also been pursued. Three materials were selected for evaluation in this program: Monarch 1100 ink grade carbon, Aldrich graphite, and Sterling RX76 carbon black. A sample of each carbon was analyzed for surface area, particle size and Scanning Electron Microscope (SEM) images were taken to determine the individual particle characteristics and morphology. The tests used 20-gauge shotgun shells loaded with the dispersing materials. Three shells of each were built with an electric match placed into the center-perforated hole. Then 2-grams of Class 7 Black Powder activator was loaded into the shell followed by the fine carbon powder. The shells were then sent for testing in an outdoor test arena. The Sterling RX76 performed the best among the three. Various small-scale formulations of a Polyglycidyl Azide Polymer (GAP) with RX76 were also made and tested. The 60/40 GAP/Carbon mix produced the best smoke out of all the formulations. However, the results of the tests indicated that when using only carbon black as the obscurant a two to four second cloud could be achieved. In addition, during all of the tests the cloud quickly changed to grey/white as the burning energetic material products dominated the smoke. Therefore, using carbon black to simulate the black smoke in this approach is not a viable alternative.

### 2.4 Physical Vaporization of Organic Dyes

Based on successful known Army utilized smoke formulations, it was determined that the environmentally benign organic dyes were most promising in producing black smoke. This method functions by forming a dye cloud via vaporizing and then condensing the dyes. Multiple color systems are most viable depending on the type of dyes and their respective amounts in formulation. For example, our black smoke is comprised of two dyes: red and green. The green M18 smoke grenade is also comprised of two dyes, green and yellow, to achieve a

distinct green color that is not obtained with the green dye alone. The advantage of using this approach is the minimization of the amount of organic compounds that are decomposed or combusted, other than the fuel, sugar. Another benefit of using the dye vaporization method in the BES systems is the reduction in the amount of smoke composition necessary, less than 50 grams per cartridge, due to a shorter burn time requirement than the M26, which contained 600 grams.

Since it is a concern that the dye will act as a fuel in the system to produce a large flame instead of smoke at elevated temperatures, a flame retardant is required in the formulation to act as a coolant. However, excess coolant will disrupt the propagation of the reaction at low temperatures. In addition, a suitable pyrotechnic base consisting of a fuel and an oxidizer, preferably the sugar and potassium chlorate, is required to generate heat for vaporization of dyes and also generate gaseous products to disperse the condensing dyes particles. Moreover, the system needs an igniter with a relatively low ignition temperature to avoid overheating of the contact smoke charge. (Conkling, 1985)

Special consideration must be taken to ensure that the formulations are safe for production and handling. Many dyes are available; however, there is some concern regarding the toxicity of the dye, often in reference to the heavy metals that are present in unprocessed dyes. However, current manufacturing technology used in organic dye production can reduce any amount of an undesired component of the dye to acceptable levels.

### 3. DYE-BASED METHOD DEVELOPMENT PROCESS

#### 3.1 Dye Selection

After the literature search and initial small-scale testing of various organic fuel / oxidizer systems, the development effort was focusing on producing a viable dye-based black smoke generating system. This process began with the selection of the dyes for further study and was determined from literature sources and/or Simultaneous DSC/TGA (Differential Scanning Calorimeter/Thermogravimetric Analysis) heat flow and weight loss thermal analysis. Suitable dyes experience significant weight loss between the melting point and boiling point. The melting points of dyes are also critical. A minimum melting point of approximately 200°C is required to ensure system stability in operating and storage conditions. Of the many types of dyes available, FD&C (Food, Drug and Cosmetic) and D&C (Drug and Cosmetic) were tested for suitability. These dyes were promising in regards to meeting health and environmental concerns as they are already found in food products and cosmetics. Unfortunately, none of the FD&C dyes met the

thermal characteristics necessary for smoke production. Also, the nature the dye enters the human body is directly related to the health and safety of the dye, in this scenario through oral ingestion or the respiration pathway. This means that although the dyes are already used in the food and cosmetics industries, they may not be acceptable to breathe. Some dyes previously used in Army smoke formulations exhibit mutagenic and/or carcinogen properties and were not examined. (Smith and Stewart, 1982) In order to mitigate the health risks of the dyes, special consideration was given to the base structure of the dye and any sub-groups present. (Deiner and Vigus, 1982)

The selected dyes (Table 3) were evaluated in a bench-scale smoke generation test, in which the sample dyes or pre-blended dye mixes were placed in a crucible and vaporized by a heat source. Dyes that generated a thick cloud in the initial crucible testing were then analyzed with the formulation development study.

Table 3: Dyes tested for smoke generation

Dye Name	Was Smoke Generated?
Foodcraft Black	NO
Spectra Black	NO
Orco Black	NO
Orco D&C Yellow 11	YES
Foodcraft Yellow 5 High	NO
Koch Black Lake Blend R	NO
Orco D&C Green 6	YES
Orco D&C Red 17	YES
Orco Smoke Red 3B	YES
Orcosmoke Violet FS	YES
Foodcraft Black Shade Dye Blend	NO
Foodcraft FD&C Blue # 1	NO
Foodcraft FD&C Red # 40	NO
Foodcraft FD&C Yellow # 6	NO
Foodcraft FD&C Yellow # 5	NO

#### 3.2 Smoke Charge Components

To analyze a potential black smoke generating system, the dye is mixed with sugar, magnesium carbonate, either potassium nitrate or potassium chlorate, stearic acid, and vinyl alcohol acetate resin (VAAR). Sugar is the preferred fuel to use with an oxidizer as a pyrotechnic base for generation of heat and gaseous products. Potassium chlorate is the current oxidizer used in most dye-based smoke formulations. (Hardt, 2001) A parallel study with two oxidizers, potassium nitrate and potassium chlorate was carried out through all stages of testing. The burn characteristics between the two oxidizers differ greatly. While potassium nitrate is the

more environmentally benign oxidizer of the two, it has failed to produce results in similar quantity and quality compared to potassium chlorate. Magnesium carbonate is the coolant used to suppress the flame. A small amount of stearic acid is added as a lubricant and processing aid. The VAAR is a binder, but also coats the mixture and prevents water degradation in the produced item. These components were selected for analysis based on previous performance in known smoke generating systems. The weight percents of each component varied according to dye performance and are unique to each dye or dye combination. Table 4 summarizes the smoke charge components and their respective role in the system.

Table 4: Components and their functions

Component	Desired Function
Organic Dyes	Color of Smoke
Sugar	Fuel
Potassium Nitrate	Oxidizer
Potassium Chlorate	Oxidizer
Magnesium Carbonate	Coolant
Stearic Acid	Lubricant/Mixing Aid
VAAR	Binder

Another common dye based smoke formulation relies on sulfur as the fuel, sodium bicarbonate as the coolant, and potassium chlorate as the oxidizer. The sugar/potassium chlorate/magnesium carbonate system and the sulfur/potassium chlorate/sodium bicarbonate systems are prevalent due to the low temperature of reaction. These pyrotechnic mixtures react in the specified temperature range to ensure that the dye vaporizes and does not combust fully. However, the second system was not considered due to the concern that a significant amount of sulfur will generate acid rain and increase the sensitivity of the smoke mix. (Hardt, 2001)

### 3.3 Smoke Mix Laboratory Manufacturing Process

The general mixing procedure for all of our dye-based mixes was that of a wet, hand-blended slurry mixing operation. Stearic acid was added to the VAAR solution (VAAR dissolved in ethyl acetate) and mixed until completely suspended in the solution. This was then mixed with the sugar until no solid agglomerates were visible and its consistency was of a wet paste. The dyes were added next. Additional ethyl acetate was required at this step because the mixture became too dry to mix homogeneously. The last additions were the oxidizer and the magnesium carbonate. Once it was determined that the wet mix was homogenous, the ethyl acetate was allowed to evaporate away to form moist smoke granules.

Some mixes, or blends, were also made with a ball mill during the initial phase of formulation development. In this case, the components were dry, no solvent was

present. The ball mill functions by rotating conductive containers containing the smoke ingredients and rubber stoppers or balls. A benefit to this method is that the overall mix time is reduced; the time to dry solvent away from the mixture is eliminated. A drawback to this method is that most binders are suspended in solution and cannot be added to the mixture. The binder adds to the strength of the pressed pellet to maintain its integrity during loading, assembly, transportation and functioning.

### 3.4 Small Scale Pellet Configuration

These dye-based formulations were pressed into a small pellet configuration (2.5-gram pellet with a 0.5-inch diameter and varying heights), with the aforementioned components. Approximately 0.5 grams of an igniter was then pressed on top of the pellet. Two different igniters, black powder and a boron/potassium nitrate (B-KNO<sub>3</sub>) igniter, were examined during this phase. The pellet testing was sufficient to determine whether or not the compositions would burn. Figure 2 illustrates the pellet configuration.

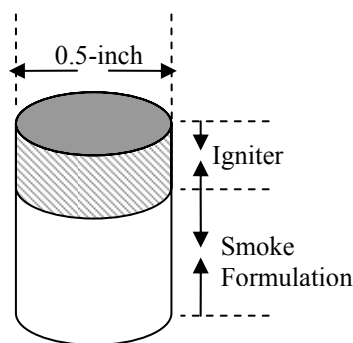


Figure 2: Small pellet (dimensions not to scale)

During testing, an electric match was placed directly on the igniter to initiate the burn. Initially, it was found that often the igniter would react too quickly to propagate the burn to the smoke composition. The testing also revealed that even when the igniter did ignite the smoke composition, the composition did not burn completely. In order to fix this problem, a more ignitable component was added to the smoke compositions to enhance the pellet burning to completion. To achieve this goal, various percentages of igniter were dry-blended into the smoke composition. The first blend tested was a 50-50 weight percent (smoke mix to igniter) with both the black powder and boron potassium nitrate igniter. It was observed that the boron potassium nitrate igniter blended with the smoke formulation caused the pellets to burn too quickly, thus producing no smoke. Unexpectedly, the black powder blends were successful in producing significant black smoke; even the smoke formulations that had potassium nitrate as the oxidizer produced a dark-grey smoke. It was determined that a 70-30 mix of the baseline smoke formulation with black powder was the

most optimal blend when potassium chlorate was the oxidizer, and a 60-40 mix was the optimal blend when potassium nitrate was the oxidizer.

There were a few drawbacks in blending black powder into the smoke base composition. First, the amount of smoke charge was significantly reduced. Secondly, an additional manufacturing step was required. Finally, the smoke quality and quantity was not as thick or dense as desired. Another concern present with the blends was that none of the igniters used at this stage proved to be consistently reliable. During this effort, some difficulties were encountered in igniting and propagating the smoke composition, as well as maintaining smoke production without partial burning or becoming too hot to combust the dyes. These difficulties were addressed by incorporating a reliable slow burning igniter patch, which is described in detail in the igniter study. In order to accurately evaluate the ignitability and performance of each black smoke system, we also needed a pellet scale with a closer corollary relation to the prototype design.

### 3.5 Initial Prototype Scale Fiberboard Testing

Several quality black smoke formulations were identified in the small pellet testing to be scaled-up to a larger center-holed pellet that was closer in size to the expected pellet size of the BES cartridge. These pellets weighed approximately 12 grams and had an outer diameter of 1.275 inches and a center-hole diameter of 0.5 inches. These pellets were pressed into fiberboard tubes. This center-hole pellet configuration is similar to the design of the M18 smoke grenade, though on a much smaller scale. Figure 3 shows the pellet with a fiberboard tube.

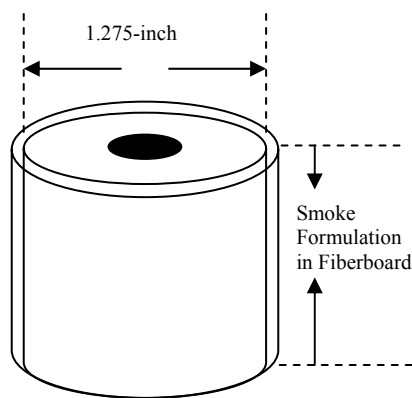


Figure 3: Prototype fiberboard pellet

During initial testing of this effort, only B-KNO<sub>3</sub> and black powder were used as igniters, the same as the small pellet testing. Due to the difficulty in igniting the pellets, different igniter application methods and various formulations were investigated to evaluate their effects on the ignition, propagation, quality of smoke and burn time.

Concurrently, 6 smoke formulations were tailored for testing with focuses on: 1) less dye to reduce the burn time while still sufficiently producing the desired color, 2) less coolant to aid in propagation and 3) more fuel and oxidizer to enhance burning to completion. An intermediate charge between the igniter and the smoke charge was also examined in addition to the two previous described methods, which were the blend method and the method of directly pressing the igniter onto the smoke charge. One mix, designated as SS-684, (with 30% dye, a 1.37 ratio of oxidizer to fuel, and 51% oxidizer and fuel) successfully met the performance requirements.

Another aspect of design that significantly altered the performance of the pellet at this stage of development was the amount of composition loaded per pellet. Pellets that weighed approximately 6 grams performed poorly overall. However, pellets weighing 10 to 14 grams performed as designed. The most common weight evaluated was 12 grams and this amount of smoke composition could easily produce 30-60 seconds of smoke.

### 3.6 Igniter Study

As part of the program objectives, in order for the system to be environmentally benign, an environmentally benign and reliable igniter must also be used. The igniter must generate enough heat with a slow ignition time to reliably initiate the smoke formulation and propagate through all of the composition without flaming.

Initially with the small pellet and the pilot-scale fiberboard pellet efforts, an increment of igniter was pressed on top of the smoke composition. The two igniters, B-KNO<sub>3</sub> and black powder, that were evaluated did not reliably ignite all of the pellets. While these igniters are relatively robust, the burn time was too short and the energy was not contained in order to propagate to the smoke composition. Both of these igniters were also applied as slurries to the surface of the pellet. The igniter slurry also contained some binder, which was to help cement the igniter as a solid to the solid pellet. The advantage to the slurry application was that there was maximum surface area between the igniter and the smoke formulation. While the slurry application showed signs of improvement, it was not sufficiently reliable. This led to the development of a slow burning and more robust igniter patch system.

As an initial igniter patch study, seven igniters were saturated into three different kinds of cloth: felt, terry cloth, and cheese cloth. It was found that both the felt and terry cloth patches with a specified weight percentage of igniter were reliable, specifically for the potassium chlorate based smoke formulations. When the igniter was able to permeate and bind to the cloth, this allowed the

igniter to burn slower than when pressed or applied as a slurry to the pellet. Figure 4 shows the desired application of a wet patch to a smoke pellet. Of the seven igniters evaluated, only two provided consistent successful results. The first successful igniter contained silicon which is an extremely hot-burning fuel. The second igniter was based on a formula already used for igniting smoke formulations, which contained a mixture of potassium nitrate, charcoal and gum Arabic binder. Of these two igniters, only the latter with the gum Arabic binder actually bonded well to the cloth. When the igniter patch was dried, the gum Arabic solidified the igniter to the fabric. The other igniters had a tendency to dry and detach from the fabric, which was a highly undesired property.



Figure 4: Igniter patch applied to pellet

Subsequent testing of multiple fabric patches helped to determine that the gum Arabic based igniter would perform well with all of the fabrics. For the simplicity of construction and consistency of size, felt was chosen as the optimal cloth to use. However, acute differences in performance between terry cloth and felt were not able to be determined from the test results.

### 3.7 Prototype Fiberboard Pellet DOE Optimization

Following the pilot scale smoke pellet studies, a smoke formulation optimization DOE (design of experiment) was developed in order to determine the ranges of weight percent for each major component of the system. The same principles regarding the relationships of the components to the performance of the smoke formulation were analyzed.

The first variable was the amount of dye in the system. Based on known dye-based smoke formulations, a reasonable range of operation is approximately 30-45 weight percent. The second variable was the total amount of fuel and oxidizer in the system. These two components are the gas generating portion of the smoke formulation and also determine the burn rate and ability to propagate the entire pellet. The operating range of this variable is approximately 39-46 weight percent. The third variable

was the weight ratio of oxidizer to fuel in the system. Generally, these components are present in weight percents close to the stoichiometric ratios. However, diverging from the stoichiometric ratios allows us to control the reaction rate as well as some burn characteristics. The components stearic acid and VAAR were held constant throughout this effort. The amount of magnesium carbonate varied along with the varying amounts of dye, fuel, and oxidizer. This study was also conducted in parallel with potassium chlorate as the oxidizer for half of the formulations and potassium nitrate for the other half.

Table 5: Variables and results of the formulation optimization study with potassium chlorate as the oxidizer

Mix	O/F Ratio	Weight % of Dye	Weight % of O/F	Black Smoke Produced?
726	1	0.35	0.39	-
727	1	0.35	0.42	-
728	1	0.35	0.46	-
729	1	0.4	0.39	-
730	1	0.4	0.42	-
731	1	0.4	0.46	Yes
732	1	0.45	0.39	-
733	1	0.45	0.42	-
734	1	0.45	0.46	-
746	1.5	0.35	0.39	-
747	1.5	0.35	0.42	-
748	1.5	0.35	0.46	Yes
749	1.5	0.4	0.39	-
750	1.5	0.4	0.42	-
751	1.5	0.4	0.46	Yes
752	1.5	0.45	0.39	-
753	1.5	0.45	0.42	Yes
754	1.5	0.45	0.46	-
764	1.75	0.35	0.39	-
765	1.75	0.35	0.42	-
766	1.75	0.35	0.46	Yes
767	1.75	0.4	0.39	-
768	1.75	0.4	0.42	-
769	1.75	0.4	0.46	Yes, flame
770	1.75	0.45	0.39	-
771	1.75	0.45	0.42	-
772	1.75	0.45	0.46	Yes, flame

The smoke formulation was analyzed with compositions determined by a 3 by 3 matrix with three levels per variable. This set of 27 mixes was repeated for each oxidizer. Each mixture produced enough composition to produce five pellets: three pellets weighed approximately 12 grams and the additional two pellets

weighed 6 grams. Two of the 12-gram pellets and one 6-gram pellet were loaded with the charcoal / potassium nitrate/ gum Arabic igniter on felt and the remaining two pellets were loaded similarly with the substitution of terry cloth for felt. Each pellet was ignited with an electric match. Table 5 summarizes the results for the formulation optimization with potassium chlorate as the oxidizer.

### 3.8 Full-up System Cartridge Testing

The final iteration of system development on the black smoke formulation and design was to integrate a full scale pellet design into an existing BES cartridge. In order to mitigate the risks of scaling-up from our fiberboard tube design to the plastic BES cartridge, three optimal formulations from the pellet optimization study (SS-731, SS-748, and SS-751) plus the optimal formulation at 30% dye (SS-684) were tested. Eight pellets of each formulation were made for the first cartridge study. Four of the pellets had an inner diameter of 0.5 inches with a weight of 13 grams, while the other four pellets had an inner diameter of 0.7 inches with a weight of 10 grams each. Each pellet was pressed with the dead load required to preserve the consolidation pressure of approximately 9,000 psi. After the pellets were pressed, the igniter patch was applied to the pellet and the pellet was immediately loaded into the BES cartridge with the patch facing down. Half of pellets in each sample group had an additional igniter patch loaded onto the top of the pellet. The inside diameter of the hole of the patches was 0.5 inches. Prior to assembling the pellet into the cartridge, the ignition interface was altered with a small hole so that an electric match could be inserted into the bottom of the cartridge as an ignition source. This step was necessary since the BES firing system was not available during this effort. A water-based adhesive was used to secure the pellets into the plastic cartridges. Prior to testing, aluminum foil was placed over the top of the cartridge with masking tape. It was determined from this test that the electric match was not the optimal way to simulate the ignition system and that a better simulation would be necessary. The formulations SS-684 and SS-751 were down-selected as the two favorable smoke formulations based on the results of this test.

The second iteration of cartridge design was to evaluate whether or not patches dried externally before loading into the cartridge would cause any difference in performance. Six pellets with the 0.5 inch diameter hole of mix SS-684 were produced. The binder of the ignition slurry sufficiently adhered the patch to the pellet. An additional 2 pellets (1 pellet each cartridge) were produced to determine the difference in consolidation pressure: 6,000 and 2,500 psi as opposed to the 9,000 psi previously used. There was no appreciable difference in

smoke performance or burn time; however, there was a significant height difference between the pellets loaded at 9,000 psi and the pellet loaded at 2,500 psi, as expected.

During this iteration the ignition system was improved to simulate the existing BES firing mechanism, in which an electric spark energy is delivered to ignite 300 mg of black powder for subsequent ignition of the smoke charge assembly. To simulate the BES firing mechanism, a quick match, instead of an electric match, was inserted into the aforementioned drilled hole and then secured with glue. Once the glue was dry, the black powder was loaded into the ignition cavity as in the existing system. Five (5) pellets were tested with this improvised ignition system. The remaining three pellets were successfully initiated with an electric match. Lids that simulated a burst-foil cap were also glued to the cartridge with a water-based adhesive. However, this glue was not strong enough to withhold the explosive nature of the black powder which expelled the lids from the cartridges. The results were as expected. There was no significant difference in the quality of smoke produced when pellets and patches were cured outside of the cartridge. In one case, the pellet was also expelled from the cartridge. This problem was rectified in the third iteration with a stronger adhesive.

The third iteration of prototype testing included multiple adjustments. The goal was to improve the black smoke quantity with a two pellet design. The final assembly of pellets in the cartridge was to emulate the current production of M34/M35 cartridges. Twelve pellets each of mix SS-684 and SS-751 were produced and 2 pellets were loaded into each cartridge. All pellets were produced with the 0.5 inch diameter hole. The pellets and patches were cured prior to loading. Three (3) cartridges of each mix were loaded with a one-piece patch-pellet-patch-pellet assembly, as demonstrated in Figure 5. The remaining 3 cartridges per mix were loaded with 2 separate patch-pellet assemblies. These pellets were glued to the cartridge with an epoxy. The inner diameter of the igniter patches was reduced from prior tests in order to mitigate the risk that the black powder would blow through the center hole without igniting the patches. The inner diameter of these patches was 0.29 inches before applying the igniter slurry. These cartridges were all altered in order to use the quick match configuration. However, several of the quick matches became too saturated with the water-based adhesive to function and were retested by inserting an electric match into the center hole which ignited the black powder. The lids of these cartridges were also secured with the epoxy. No lids were expelled during testing. The results of this test were similar to previous tests. Both formulations produced a dark-grey/black smoke for 20 to 40 seconds. However, there was still some cartridge deformation present after testing. It is believed that the actual BES firing system



and the silicone sealant will keep the smoke from channeling up the walls of the cartridge and deforming the plastic cartridge. The firing hardware may act as a sufficient heat sink to prevent the cartridges from deforming to the point where they cannot be removed from the system.

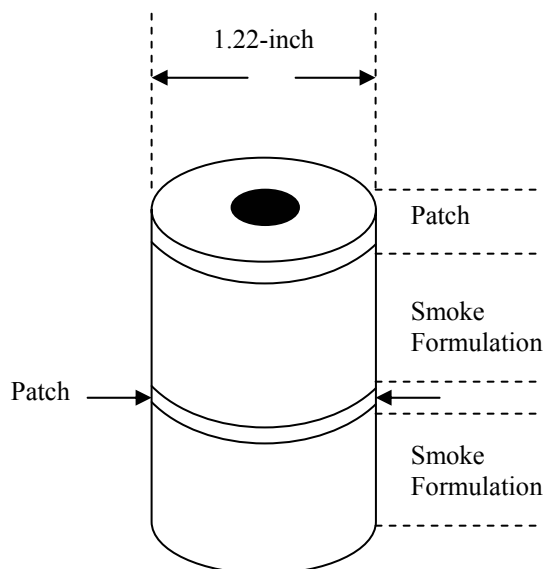


Figure 5: Final design of smoke pellet

## CONCLUSIONS

In summary, an environmentally benign black smoke composition has been developed using an organic green and red dye mix with a sugar and potassium chlorate pyrotechnic base. The composition is initiated with a reliable igniter patch system in which the fabric patch burns several seconds after initiation to generate a quality black smoke cloud by vaporization and condensation of the dyes. This technical approach will significantly reduce the environmental and health hazards of the combustion species compared to the existing and other experimental methods. The developed black smoke prototype design is currently being transitioned to a production environment for a full-up system prove-out and demonstration. The ultimate program goal is to integrate it into the BES system to provide our troops with effective pre-deployment training.

## ACKNOWLEDGMENTS

The authors of this paper would like to acknowledge the following individuals for their supports and contributions to the black smoke simulator development effort: Maryalice Miller, William Ruppert, Joseph Domanico, Eric Latalladi, Mike Saski, and Mike Hartley.

## REFERENCES

- Conkling, J. A., 1985, Smoke and Sound. *Chemistry of Pyrotechnics: Basic Principles and Theory*. 167-179.
- Deiner, A and Vigus, E. S., 1982: Evaluation of Replacement Red Smoke Dyes for 1-Nmethylaminoanthraquinone, *Eighth International Pyrotechnics Seminar*. 149-158.
- Hardt, A. P., 2001: Generation of Smoke. *Pyrotechnics*. 319-332.
- Smith, M. D. and Stewart, F. M., 1982: Environmentally Acceptable Smoke Munitions, *Eighth International Pyrotechnics Seminar*. 623-635.