Health Effects from Theatrical Pyrotechnics

Monona Rossol
181 Thompson St. #23, New York, NY 10012 USA

ABSTRACT

Theatrical pyrotechnics are potentially capable of creating ear-damaging sound, eye-damaging light, and airborne toxic chemicals. While damage to the ears and eyes can be dramatic and obvious, potential health problems from inhalation of the smoke are not so easily addressed. The problem is further complicated by the variety of locations in which pyrotechnics are used. A few examples are theaters, theme parks, outdoor arenas, and both indoor and outdoor movie and TV filming locations.

For these reasons, this article will consider the hazards of chemicals used in consumer fireworks, specialized indoor theatrical effects and professional outdoor effects. The article also will include material that is well-known to pyrotechnicians since readers from the theatrical and entertainment industries may find this background information helpful.

Keywords: theater, pyrotechnics, entertainment, health, toxicity, safety, smoke

Introduction

My interest in pyrotechnics began in earnest in January of 1987 when I spoke at the "Health and Safety Conference on Personal Protection and Pyrotechnic Training" hosted by the Yale School of Drama's Department of Technical Design and Production. My talk on potentially toxic and irritating emissions from pyrotechnic products was met with skepticism until the demonstration of indoor effects at the end of the conference. Then a steady crescendo of coughing from the audience made the point effortlessly.

Pyrotechnic Hazards

When indoor and outdoor pyrotechnic effects are used in close proximity to performers and shooters, there is no question that the chemicals in the smoke can be harmful. What is not clear is whether these chemicals are present in significant quantities in theatrical venues to affect health. This issue is not likely to be settled soon since I am unaware of any studies of performers exposed to indoor and outdoor pyrotechnics currently underway.

The only studies I could find from the past were two very limited ones done in 1981 and 1982, both of which are discussed in a National Institute for Occupational Safety and Health (NIOSH) health hazard evaluation report related to pyrotechnics used at the MGM Grand Hotel and Casino in Las Vegas.[1a]

The MGM Grand Hotel Studies

In 1981, the Nevada Department of Occupational Safety and Health (DOSH) responded to worker complaints about smoke from pyrotechnics used in the show, Jubilee, in the Ziegfeld Showroom of the MGM Grand Hotel in Las Vegas. DOSH tested the air and found that the airborne particulates in the smoke consisted of several chemicals some of which were alkaline. There were no industrial standards that applied to any of these chemicals. DOSH then could only apply the Occupational Safety and Health Administration (OSHA) nuisance dust standard to their findings. This standard allows workers to be exposed to 15 milligrams per cubic meter (mg/m^3) of ordinary-sized nuisance dust particles, and to 5 mg/m^3 of respirable dust (particles under 10 microns in diameter).

The NIOSH researchers point out that this 15 mg/m^3 standard is not sufficiently protective, especially for substances that are alkaline.[1b] In addition, the majority of the particulates from pyrotechnics are likely to be very small and should be regulated by the respirable dust standard. However, DOSH researchers sampled without characterizing particle size, the total dust standard was not exceeded, and DOSH could take no further action.

Then in 1982, NIOSH received a request from a local union to evaluate complaints of respiratory difficulties, sinus problems, eye irritation, and nausea among the approximately 150 stagehands, wardrobe attendants, and performers at the same show. Arrangements were made for a NIOSH physician to interview a self-selected group of 16 workers. Based on the information obtained during these interviews and from contacts with the workers' private physicians following the interviews, an Interim Report was sent to all concerned parties. The report suggested that the cases of respiratory problems and bronchitis found among the workers indicated that a health hazard did exist in the show.

NIOSH proposed further study including air sampling, but MGM refused to allow NIOSH to make a site visit. (NIOSH is not a regulatory agency and needs the employer's permission to enter the workplace.) In addition, the manufacturers of the pyrotechnic materials would only supply NIOSH with the "general composition of the various types of mixtures used and the expected decomposition products"[1c] because their products were considered trade secrets. From the limited available data, NIOSH concluded in their Final Report that:

> *There is a health hazard due to the alkaline dust produced by the pyrotechnics in the "Jubilee" show. There is also a possibility that the potassium sulfate which is probably present in the smoke is at least in part responsible for the bronchitis. A 10% incidence of respiratory problems, some being a bronchitis, is excessively high. This represents a minimum incidence although all of the more serious cases may be included in this sample. The rashes mentioned by wardrobe attendants and performers may also be due in part to the alkaline dust.*[1d]

The report caused MGM to modify pyrotechnic use during the show and to allow the use of respirators by some of the stage hands. A NIOSH follow-up telephone survey of the workers previously interviewed confirmed that the changes MGM made improved conditions.

What Is in the Smoke?

It is difficult to determine the chemical composition of pyrotechnic emissions. Books on pyrotechnic chemistry have examples of neatly balanced chemical reactions that are predicted to occur when you mix part–A with part–B and ignite. In practice, the reactions are not this simple. Pyrotechnic ingredients are not pure chemicals. In addition, most theatrical pyrotechnic products are highly modified and adulterated to produce colored smoke, flash, "flitter," or other special effects.

For example, the NIOSH researchers in the MGM Grand study showed that the solid decomposition products seen as smoke or found settled on surfaces as a fine gray dust consisted of a complex mixture of aluminum and titanium oxides, strontium carbonate, carbon, strontium chloride, potassium chloride, potassium sulfate, strontium hydroxide and potassium carbonate. Clearly, the metals involved in the reaction formed many different combinations with oxygen, carbon, and chlorine. The presence of strontium suggests the mixture was modified for effect.

When asked about the gasses released by the pyrotechnic mixture used at the MGM Grand, the pyrotechnic manufacturer referred NIOSH to studies of high quality commercial black powder which showed that primarily nontoxic gases like nitrogen and carbon dioxide were produced on combustion.

However, the composition of the dust from the MGM effects and the MSDSs indicate that they were certainly not anything like simple black powder. It is more likely that the MGM effects produced sulfur oxides, nitrogen oxides, carbon monoxide, hydrogen sulfide, and more.

What Are Pyrotechnics Made of?

The oldest pyrotechnic material probably is gunpowder, a variety of what is known as *black powder* or *blasting powder.* In these products, all the substances necessary for the reaction are premixed together and ready for ignition. In general, they are:

potassium nitrate + sulfur + charcoal

$KNO_3 + S + C_{(80–85\%)}$

If this reaction were ideal, the resulting "smoke" solids would be potassium compounds and the gases released would be primarily nitrogen and carbon dioxide. However, most gunpowder and black powder explosions also produce hydrogen sulfide, sulfur oxides, carbon monoxide, and methane.[2]

Powder for theatrical gunfire also can be modified for effect. Adding more carbon produces more visible gunsmoke that simultaneously creates more carbon monoxide and respirable particulates. If aluminum and/or magnesium metals in powdered form are added, the resulting powder also produces aluminum and magnesium compounds.

Modification for Effects and Color

Other types of indoor and outdoor pyrotechnics can be modified by the addition of many substances. "Sparkling" effects are produced when particles of various metals or alloys are added. Color may be produced when compounds containing certain metals are added. Table 1 contains a partial list of the chemicals that will allow various pyrotechnic mixtures to create colored flame or flash effects.

Colored smokes can be produced by adding an organic chemical dye to a pyrotechnic mixture that volatilizes the dye but does not decompose it. The complex organic dyes used for smoke are of low acute toxicity, but some, especially the anthraquinones, are probably carcinogens.

The National Toxicology Program (NTP) has slated six natural and synthetic anthraquinone dyes and intermediates for study to determine if the entire class is suspect.[3] Four have been studied and found to cause cancer: l-amino-2,4-dibromoanthraquinone (CAS 8l-49-2),[3] 2-aminoanthraquinone (CAS 117-79-3)[4a] and 1-amino-2-methylanthraquinone (CAS 82-28-0),[4b] and Disperse Blue 1 which is l,4,5,8-tetra-aminoanthraquinone (CAS 2475-45-8).[5] And this year, NTP proposed listing 1,8-dihydroxy-anthraquinone (CAS 117-10-2) in the ninth report as "reasonably anticipated to be a human carcinogen."[6]

Another smoke dye that is not an anthraquinone also may be a carcinogen. It has several names including CI Solvent Yellow 33, Quinoline yellow, and D&C Yellow No. 11 and has showed some evidence of carcinogenic effects in both sexes of rats.[7]

Some dyes are also likely to partially break down to release toxic chemicals such as aniline during the reaction or during metabolism in the body if inhaled. Some of these dyes and other smoke colorants are listed in Table 2.

Table 1. Flash and Flame Colorants.

Red	Strontium compounds (e.g., nitrate, carbonate, sulfate)
Orange	Calcium compounds (e.g., carbonate, sulfate)
Yellow	Cryolite (sodium aluminum fluoride), sodium compounds (e.g., nitrate, oxalate, sulfate)
Green	Barium compounds (e.g., nitrate, carbonate, sulfate, chlorate), borax
Blue	Copper compounds (e.g., carbonate, chloride, oxide, oxychloride) cupric acetoarsenite*
Violet	Potassium nitrate, lithium chloride

* also called Paris Green (used in some foreign and commercial fireworks)

Table 2. Smoke Colorants.

Orange	CI Pigment Orange 7 [15530]* a monoazo dye
	CI Solvent Orange 86 [58050],* an anthraquinone dye (also used in emergency orange smoke flares)
Green	CI Solvent Green 3 [61565],* an anthraquinone dye
Red	CI Disperse Red 9 [60505], an anthraquinone dye
	Safranine: any of nine Basic dyes in the phenylsafranine class [50200-50375]*
Violet	1, 4-diamino-2, 3-dihydroanthraquinone (an anthraquinone related to CI Disperse Violet 1)
	Iodine in various compounds (probably not used today except by some stage magicians for small effects)
Yellow	CI Vat Yellow 4 [59100]*
	CI Solvent Yellow 33 [47000]* also called "Quinoline yellow" and D&C Yellow 11
	CI Basic Yellow 2 [41000]* also called "auramine"
	Arsenic disulfide (realgar — used in some foreign and commercial fireworks)
White	Phosphorus, inorganic chloride such as ammonium chloride or zinc chloride.

* These dyes are identified by their Color Index (CI) names and [constitution numbers]. This internationally accepted method of classification enables readers to look up the dye's chemical structure.

Pyrotechnic Chemical Classes and Their Emissions

Hundreds of chemicals can be used in indoor and outdoor pyrotechnics. Each chemical has one or more functions in the chemical reactions that occur on combustion. Most common pyrotechnic mixtures consist of an oxidizer, a fuel, a source of carbon, and various additives such as chlorine donors to enhance color and other chemicals to modify appearance or sound. Pyrotechnic chemicals can be grouped by these basic functions as follows.

Oxidizers

Oxidizing agents are usually metal nitrates, oxides, peroxides, chlorates, perchlorates, and chromates. Almost any metal in the periodic table can be present in oxidizers (see Metals below). Reaction may produce metal oxide fumes, metal chlorides, and compounds related to decomposition of nitrate, chlorate, and other radicals.

Fuels (electron donors)

The reaction is fueled by electrons donated from finely divided metals such as powdered aluminum, iron, magnesium, titanium, tungsten, zinc, and zirconium, or nonmetals such as boron, sulfur, phosphorus, and silicon. Reaction may produce metal oxide fumes, phosphoric acid, sulfur oxides, and silica.

An important subclass of fuels are **Carbon Suppliers**. These may be sugars, starches, epoxy and polyester resins, naphthalene, anthracene, and many solvents. Often carbon suppliers are overlooked as sources of toxic emissions other than carbon monoxide and carbon dioxide. Yet highly toxic substances are emitted by all natural and synthetic carbon-containing substances. It matters little if you burn coal, oil, wood, incense, hamburger, or tobacco. Just because we like the smell of incense or burning autumn leaves does not make their smoke healthier.

In fact, studies show that traditional open burning of leaves in the fall generates dangerously large quantities of carbon monoxide, particulates, and at least seven proven carcinogens. This leaf-burning pollution severely increases breathing problems in a majority of asthmatics in the fall.[8] Similarly, burning naphthalene and anthracene to produce black smoke in outdoor movie scenes releases cancer-causing benzene and polycyclic aromatic hydrocarbons.

Carbon-containing pyrotechnic effects also produce these toxic emissions. In fact, the greater the amount of excess fuel in the formula and the lower the temperature at which it burns the greater the production of polycyclic aromatic hydrocarbons and other toxic chemicals. Theatrical effects are particularly likely to be modified in this way.

If the carbon suppliers are solvents that also contain chlorine, they will emit additional toxic substances (see chlorine suppliers below).

Additives

Chlorine (and other halogen) suppliers include chlorinated rubber or plastics such as polyvinylidine chloride (Saran) or polyvinylchloride (PVC), inorganic metal chlorides, chlorates, or perchlorates, dechlorane (Mirex), hexachlorobenzene, carbon tetrachloride, perchloroethylene, and many other chlorinated hydrocarbons. Sometimes other halogens are used such as fluorine in the form of fluoride, bromine, or iodine compounds. Most of these chemicals are very toxic, some are carcinogens, and some (e.g., Mirex and hexachlorobenzene) also are EPA-registered pesticides. Reaction converts them into many hazardous halogen-containing compounds that may include hydrochloric acid, hydrofluoric acid, and phosgene.

Metals. Metals or metallic compounds have many functions including as oxidizers (see above), fuel (see above), flash, or smoke colorants to affect light intensity, sparkle, or for other effects. Some very toxic metals commonly used in fireworks include lead, arsenic, barium, boron, antimony, manganese, mercury, chromium, and copper. After combustion, these metals can be found in the smoke as a fume or settled out on surfaces as a fine dust. Even when metals are in amounts too small to cause toxic reactions, they may cause serious allergies. Some metals, especially chromium, are well-known sensitizers.

Silica. Silicon (Si), used as a fuel, will convert to silica (silicon dioxide — SiO_2) during combustion. It is likely to be emitted in the rather toxic fume form (see Table 3).

Silicon dioxide is also added to some pyrotechnic mixtures in amounts usually ranging from 0.1 to 1.5 percent. Any dust containing more than one percent crystalline silica warrants concern. A pyrotechnic formula containing one percent silica is likely to produce solid emissions containing more than one percent silica since the silica will persist while other substances will decompose or become gaseous.

Table 3. Threshold Limit Values* of Various Forms of Silica.

SUBSTANCE	TLV–TWA* (1996 values) milligrams/meter^3
silicon — Si	10
amorphous silica – SiO_2	
diatomaceous earth	10
silica fume	2
crystalline silica – SiO_2	
quartz	0.1
tridymite & cristobalite	0.05

* Threshold Limit Values (TLVs) are workplace air quality standards set by the American Conference of Governmental Industrial Hygienists, 1330 Kemper Meadow Drive, Cincinnati, OH 45240. TLVs are designed to protect the majority of healthy adult workers from adverse effects. The TLV–TWA is a time weighted average of airborne concentrations averaged over the eight hour work day.

While it is likely that amorphous silica in the pyrotechnic formula would be emitted still in the amorphous form after combustion, I have not been able to find any actual confirmation of this assumption. This is clearly an important question to answer because the different forms of silica vary greatly in toxicity.

Other Chemicals include explosive chemicals such as TNT (trinitrotoluene) and nitroglycerin, thiocyanates of mercury, antimony, and other metals, various amines such as hexamethylene tetraamine and triethanolamine, and an EPA-registered pesticide called cryolite (sodium aluminum fluoride).

Flash Paper is nitrocellulose which burns with a flash on ignition. Colorants also may be added. The decomposition products of flash paper include toxic and irritating oxides of nitrogen. Used in small amounts it is not very hazardous. For larger amounts such as those used in flitter, fountains, waterfalls, and flamepots, the emissions could be significant.

Organic Pigments and Dyes used to color the smoke may also be present (Table 2). These usually are carbon-containing substances and their hazards are similar to those listed above under Fuels (carbon suppliers).

Health Effects Related to Pyrotechnic Smoke

The only sure way to assess the health effects of a particular pyrotechnic "smoke" is to analyze it and research the health effects associated with each component. Ethically, this should be done before exposing performers, but it is not likely to happen. However, some generalizations can be made about potential health effects.

1. Respiratory and eye irritation can occur from exposure to pyrotechnic smoke. Many of the solid particulates and gases are irritating and some are outright corrosive such as many of the chlorine-, nitrogen-, and sulfur-containing acid gases.
2. Acute and chronic allergic responses of the respiratory system, eyes, and skin can occur from exposure to pyrotechnic smoke. Many of the solids and gases are sensitizing, including those containing chromium compounds and the sulfur oxides. The dyes used to color smoke also may be sensitizers.
3. Acute and chronic systemic toxicity are associated with exposure to small amounts of lead, arsenic, barium, mercury, antimony, and some other metals. Chronic toxicity affecting the nervous system can be caused by some metals including lead, mercury, and manganese.
4. Cancer is associated with many of the metals, chlorine compounds, and organic chemical dyes.
5. Long-term lung problems are associated with the inhalation of fine dusts of silica, aluminum oxide, and other inert compounds.

Hazard Assessment

The first step in determining the hazards of a particular effect is to identify its ingredients. Unfortunately, most pyrotechnics are considered trade secrets, and product labels and the manufacturer's material safety data sheet (MSDS) will not list the ingredients. The MSDS also is supposed to list the hazardous decomposition products, but most do not. Those MSDSs that do list them may be reporting only a theoretical guess.

Another unique problem with both MSDSs and the pyrotechnic literature is that chemicals may be identified by traditional names that hark back to medieval alchemy. For example, mercurous chloride may be called *calomel,* mercuric sulfide may be called *quicksilver vermilion,* ammonium chloride may be called *sal ammoniac*," and arsenic disulfide may be called *realgar.* While the words can be looked up in chemical dictionaries, performers and other theater workers usually do not have ready access to these references and can be misled by this outdated terminology.

Most MSDSs do list highly toxic metals present in the mixture even if they do not identify the exact compounds in which they are present. This, at least, gives users the opportunity to reject highly toxic products.

Precautions for Pyrotechnic Use

1. Evaluate MSDSs and reject effects containing especially dangerous substances such as highly toxic metals (lead, mercury, etc.) and known carcinogens. Assume the smoke and gases released by all pyrotechnics are toxic since they almost assuredly are.
2. Inform performers at audition about the nature of the effects that will be used. Inform the public at the ticket office that pyrotechnic effects will be used on-stage that produce light, sound, and smoke.
3. Assume that exposure is most significant near the effect shortly after combustion. Make provisions for reducing workers' exposure by blocking performers far away from effects and by allowing other personnel to wear respiratory protection.

4. Set up ventilation fans and systems to remove the smoke from the stage and adjacent areas quickly and to keep smoke from entering the house and exposing the audience. Prevailing winds and terrain must be considered when planning outdoor effects.
5. Inform and train all potentially exposed personnel about pyrotechnic hazards and provide them access to the MSDSs as required by law.[11]
6. Make provisions for medical evaluation and treatment of any cast or crew member who requests it and keep accurate records of any possibly related illness as required by law.[11] Provide workers with access to their medical records as required by law.[11]

The Most Important Precaution

Unfortunately, the "macho" approach to pyrotechnics is still alive and well. Complaints from performers and other personnel often are not taken seriously. This author is personally aware of situations in which performers complaining about special effects exposures have been derided, fired, and even blacklisted.

Instead, the potential hazards of pyrotechnics must be accepted as a legitimate concern. The most effective method of preventing health effects from pyrotechnic exposure is to obtain a commitment from special effects directors, company managers, and primary employers that the health of the cast and crew must come before any artistic or financial consideration.

References

1) National Institute for Occupational Safety and Health Hazard Evaluation Technical Assistance (HETA) 82-365-1282, "Health Hazard Evaluation Report on the MGM Grand Hotel and Casino in Las Vegas, Nevada," NIOSH, p 5, 3, 7, 1982. Note: Curiously, the show under study was the first one to open after the famous and deadly 1980 MGM Grand fire.

2) Davis, Tenney L., *The Chemistry* of *Powder and Explosives,* Angriff Press, Hollywood, CA, 1945, p 43.

3) *Bureau of National Affairs–Occupational Safety and Health Reporter,* Vol. 24, No. 5, June 29, 1994, p 268.

4) *Seventh Annual Report on Carcinogens,* Summary, 1994, National Toxicology Program, US DHHS, pp 87–89, 90–91.

5) Federal Register, Vol. 56, No. 151, Tuesday, August 6, 1991, pp 37366–37367.

6) *Bureau of National Affairs-Occupational Safety and Health Reporter*, Vol. 25, No. 49, May 15, 1996, p 1706–7.

7) *Bureau of National Affairs–Occupational Safety and Health Reporter,* Vol. 25, No. 28, December 13, 1995, p 975.

   Note: the study reported was a National Toxicology Program study that found "some evidence" of carcinogenic activity. The NTP uses five categories of evidence in animal studies:

   Two categories for positive results ("clear evidence" and "some evidence"); one category for uncertain findings ("equivocal evidence"); one category for no observable effects ("no evidence"); and one category for studies that cannot be evaluated due to major flaws ("inadequate study").

8) Luke Curtis, "The Health Hazards of Leaf Burning," *The American Journal of Public Health* Vol. 84, No. 10, 1994, p 1696.

9) OSHA General Industry Standards 29 *Code of Federal Regulations* 1910.1200. If the pyrotechnic display is outdoors, the hazard communication requirement is the same, but it is found in the OSHA Construction Standards at 1925.59.

10) 29 *Code of Federal Regulations* 1904.

11) 29 *Code of Federal Regulations* 1910.20.

Suggested Reading

"Theatrical Fogs and Smokes: A Report on Their Hazards," Monona Rossol, American Guild of Musical Artists, in cooperation with AEA, SAG and AFTRA, New York, 1991.

Chemistry of Pyrotechnics, John A. Conkling, Marcel Dekker, New York, 1985.

"Introductory Chemistry for Pyrotechnists, Part 1: Atoms, Molecules, and Their Interactions," Wesley D. Smith, *Journal of Pyrotechnics,* Issue No. 1, 1995, pp 19–25.

"Introductory Chemistry for Pyrotechnists, Part 2: The Effects of Electrons," Wesley D. Smith, *Journal of Pyrotechnics,* Issue No. 2, 1995, pp 15–35.

"Prediction of Flame Temperatures, Part 1: Low Temperature Reactions," Daniel P. Dolata [Thomas I. Perigrin], *Journal of Pyrotechnics,* Issue No. 1, 1995, pp 37–46.

American Fireworks News, collected issues from 1989 through 1995.

Creating Special Effects for TV & Films, Bernard Wilkie, Focal Press (Butterworth Group), London, 1977.

The Illustrated Dictionary of Pyrotechnics, K.L. and B.J. Kosanke, Journal of Pyrotechnics, 1995.

Lecture Notes for the Pyrotechnic Chemistry, K.L. and B.J. Kosanke, Journal of Pyrotechnics, 1996.