Fire Safety in Consumer Fireworks Storage and Retail Facilities – Hazard Assessment Research Project

Literature Review

Prepared by:

Schirmer Engineering Corporation

THE
FIRE PROTECTION
RESEARCH FOUNDATION

FIRE RESEARCH

THE FIRE PROTECTION
RESEARCH FOUNDATION

ONE BATTERYMARCH PARK
QUINCY, MASSACHUSETTS, U.S.A. 02169
E-MAIL: Foundation@NFPA.org
WEB: www.nfpa.org/Foundation

FOREWORD

In 1999, the scope of NFPA 1124 was expanded to include requirements for retail sale of consumer pyrotechnics and the Pyrotechnics Committee was charged with the development of a new chapter on consumer fireworks retail sales facilities In 2003, the first version of the standard was published with a new Chapter 7, covering permanent facilities (both fireworks only and mixed commodity facilities), temporary stands, tents and other retail sales facilities. To assist the Committee, in 2007, NFPA commissioned this study to assemble research data related to the hazards associated with retail sale of consumer fireworks and identify research needed to develop appropriate facility fire safety provisions. The study includes a review of available literature on fire incidence, characterizing of the hazard, and relevant international and analogous code provisions, and recommends further research to further develop the technical basis for Chapter 7 provisions.

The Research Foundation expresses gratitude to:

The report author Jonathan Perricone; the Project Technical Panel (listed on following page), and the National Fire Protection Association.

The content, opinions and conclusions contained in this report are solely those of the author.

Fire Safety in Consumer Fireworks Storage and Retail Facilities – Hazard Assessment Research Project

Technical Panel

Elizabeth Buc, Fire and Materials Research Lab, LLC

John Conkling

Ettore Contestabile, Canadian Explosives Research Lab

William Koffel, Koffel Associates, Inc.

Kenneth Kosanke, PyroLabs, Inc.

John Robison, Robison Consulting

William Thomas, TVA Fire & Life Safety, Inc.

Alexander van Oertzen, Federal Institute for Materials Research and Testing

Guy Colonna, NFPA Liaison

Principal Sponsor

National Fire Protection Association

SCHIRMER ENGINEERING
11770 Bernardo Plaza Court, Ste. 116
San Diego, CA 92128
Phone (858) 673-5845 Fax (858) 673-5849

Fire Protection ■ Code Consulting ■ Risk Control ■ Security Consulting

Final Report

LITERATURE REVIEW: FIRE SAFETY IN CONSUMER FIREWORKS STORAGE AND RETAIL FACILITIES – HAZARD ASSESSMENT

SEC Project No.: 2007069-000

Prepared For:

Fire Protection Research Foundation

October 1, 2007

TABLE OF CONTENTS

EXECUTIVE SUMMARY – FINAL RECOMMENDATIONS .... - 1 -
PROJECT OBJECTIVES .... - 3 -
INTRODUCTION .... - 4 -
DEFINITIONS .... - 5 -
DOMESTIC AND INTERNATIONAL FIRE INCIDENT RESEARCH .... - 7 -
  Scottown, Ohio – July 3, 1996 .... - 10 -
  Tultepec, Mexico – September 15, 2005 .... - 12 -
  Introduction for Analogous Commodity Incidents .... - 13 -
  Falls Township, Pennsylvania – June 21, 1982 .... - 16 -
  Phoenix, Arizona – August 2, 2000 .... - 19 -
  Loss History Conclusion .... - 21 -
FIRE RESEARCH AND TEST DATA .... - 22 -
  Enthalpy of Combustion .... - 23 -
  Reaction Temperature .... - 23 -
  Reaction Rate and Flame Spread .... - 24 -
  Composition of Reaction Products – Issues of Tenability .... - 26 -
  Sensitivity and Explosiveness .... - 30 -
  Effects of External Fire on Fireworks Stored in Steel Transport Containers .... - 31 -
  Enclosure Fire in Simulated Consumer Fireworks Retail Setting .... - 34 -
  Packaging Effects .... - 37 -
  Effectiveness of Automatic Sprinkler Systems .... - 38 -
  Fire Protection Engineering Design for Large Distribution Centers .... - 42 -
HAZARD DATA .... - 44 -
  Flash Powder .... - 44 -
  U.N. Scheme for the Transport of Dangerous Goods .... - 45 -
  Classification of Fireworks in the United States .... - 48 -
  Authorization and Classification of Fireworks in Canada .... - 49 -
  Classification of Fireworks in the United Kingdom .... - 50 -
  Classification of Fireworks in Japan .... - 51 -
RELEVANT CODE PROVISIONS FROM OTHER (INTERNATIONAL) CODES .... - 52 -
  2006 International Building Code (IBC) .... - 52 -
  2006 International Fire Code (IFC) .... - 54 -

Regulations of the International Community .... - 56 -
RELEVANT CODE PROVISIONS FOR ANALOGOUS HAZARDOUS COMMODITIES....... - 57 -
Fundamental Commodity Hazards .... - 59 -
Storage Arrangement and Quantity .... - 60 -
Fire Prevention Measures.. - 61 -
Output .... - 62 -
Protection Objectives Specific to Combustion.. - 62 -
Protection Objectives Specific to Combustion Effects .... - 63 -
CONCLUSIONS... - 63 -
NFPA 1124 Provisions for Storage of Consumer Fireworks... - 63 -
NFPA 1124 Provisions for Retail Sales of Consumer Fireworks .... - 64 -
REFERENCES 1

INDEX OF TABLES

TABLE 1A. SIGNIFICANT DOMESTIC INCIDENTS .... - 8 -
TABLE 1B. SELECTED INTERNATIONAL INCIDENTS$^{,,\ ,}$ .... - 10 -
TABLE 2. LARGE LOSS AEROSOL FIRES IN THE UNITED STATES .... - 16 -
TABLE 3. COMMONLY USED FIREWORKS CHEMICALS .... - 28 -
TABLE 4. SWEDISH CONSUMER FIREWORKS CHEMICAL ANALYSIS* .... - 29 -
TABLE 5. SIGNIFICANT PRODUCT EMITTED FROM BURNING FIREWORKS[37] .... - 29 -
TABLE 6. FIREWORKS LOAD IN UK TEST .... - 32 -
TABLE 7. POLISH CONSUMER FIREWORKS USED IN CHAF TEST.............................. - 33 -
TABLE 8. TIMELINE OF RESULTS FROM POLISH CONSUMER FIREWORKS TEST..... - 33 -
TABLE 9. LOADING OF SIMULATED RETAIL FIREWORKS STAND................................ - 34 -
TABLE 10. TIMELINE OF EVENTS FOR FIREWORKS STAND EXPERIMENT................. - 35 -
TABLE 11. BATTELLE FULL SCALE WET PIPE TEST TIMELINE.................................... - 41 -
TABLE 12. UN CLASSIFICATION OF DANGEROUS GOODS (EXPLOSIVES) .... - 45 -
TABLE 13. UN DEFAULT CLASSIFICATION TABLE (1.4G CLASSIFICATIONS).............. - 47 -
TABLE 14. DIFFERENCES BETWEEN UN 1.4G AND CANADIAN 7.2.1 .... - 50 -
TABLE 15. CRITERIA FOR UK HAZARD TYPE 4 .... - 51 -
TABLE 16. IFC TABLE 3301.8.1(3) APPLICATION OF SEPARATION DISTANCES.......... - 55 -
TABLE 17. IFC TABLE 3304.5.2(3) TABLE OF DISTANCES .... - 56 -
TABLE 18. CONCEPTUAL COMPARISON OF ANALOGOUS HAZARDS .... - 58 -

INDEX OF FIGURES

FIGURE 1. PREPARATION FOR NATIONAL PYROTECHNICS FESTIVAL .... - 12 -
FIGURE 2A. RETAIL FIREWORKS IN MODULAR TRAILER .... - 14 -
FIGURE 2B. RETAIL FIREWORKS IN STRIP-MALL .... - 14 -
FIGURE 2C. RETAIL FIREWORKS IN MEMBRANE STRUCTURE .... - 14 -
FIGURE 3. TEMPERATURES DURING FIREWORKS STAND EXPERIMENT .... - 35 -
FIGURE 4. TRANSIENT HEAT FLUX DURING FIREWORKS STAND EXPERIMENT .... - 36 -
FIGURE 5. SPATIAL HEAT FLUX PROJECTED FROM EXPERIMENTAL DATA .... - 36 -
FIGURE 6. BATTELLE SHOWROOM LAYOUT... - 40 -
FIGURE 7. UN PROCEDURE FOR ASSIGNMENT TO A DIVISION OF CLASS I .... - 46 -

EXECUTIVE SUMMARY – FINAL RECOMMENDATIONS

The objective of this review was to assemble and analyze research data related to the hazards associated with retail sale and storage of consumer fireworks and to identify research needed to develop appropriate facility fire safety provisions. Based on this review, the recommendations are as follows:

1. Consumer fireworks, by definition, are meant to exclude high-energy explosives, which are known to yield explosive behavior on a potentially destructive scale. This is the primary reason behind the scarcity of loss history for fire in the built environment involving this commodity. More research is recommended for evaluating the energetic properties of small amounts of flash powder in order to maintain the intent of this classification as the industry develops.

2. All of the domestic incidents documented in this report were initiated by arson and in some cases the outcome was exacerbated by negligence (i.e., disabled sprinkler system). This supports an increased focus on inspection, security and safety training of personnel, which is reflected in current NFPA 1124 requirements.

3. Removal of heat from the reaction zone appears to be the most efficient means for disrupting the combustion process in consumer fireworks. This may be achieved most practically with the application of water by automatic fire sprinklers. The universal objectives for automatic sprinkler protection are identified by NFPA 13 *Standard for the Installation of Sprinkler Systems* as either fire suppression or fire control depending on the application. Achieving complete fire suppression may not be necessary for meeting the exclusive objective of life safety in this application. Fire control is defined in part as decreasing the heat release rate of burning commodity and slowing flame spread by wetting adjacent combustibles. Consequently, experimental data on the heat release rate of packaged consumer fireworks is needed. Such data may be obtained experimentally with the use of a cone calorimeter.

4. The heat release rate of a burning commodity is influenced by storage arrangement parameters such as the height of commodity and radiant thermal feedback from surroundings. Such effects have been established for fires involving a range of hydrocarbon fuels. These trends may also apply to packaged consumer fireworks, though validation is appropriate. Estimation of the heat of combustion of the commodity (Equation 1) may be useful for relative comparison to established commodity classification schemes.

5. Flame temperature is a primary mechanism for flame spread across a solid surface. The range of adiabatic flame temperatures estimated for pyrotechnic compositions (Equation 2) implies potentially faster flame spread for this commodity in storage configurations as opposed to ordinary combustibles. Packaging of the commodity acts as a weak insulator of a strength determined by the ratio of thickness versus thermal conductivity. As this ratio is increased (i.e., material change), so too is the resistance to heat conduction. Similarly, an increase in density of a solid slows the rate of flame spread across the surface (Equation 4). These principles may be applied both to the insulating quality of packaging and also to the design of flame breaks and covered fuses. Note that such features may be quite effective when the

heat source is small, but as the fire grows, the insulating strength of materials used becomes much more significant.

6. Data on the composition and toxicity of combustion products for consumer fireworks is necessary for estimating tenable conditions during a fire event in a retail sale facility. Such data may also be obtained experimentally with the use of a cone calorimeter, similar to the experiments conducted by Marlair[37]. Once smoke generation is quantified, propagation may be modeled as a basis for evaluation of design methods for smoke removal from a facility.

7. Facility specific research regarding the maximum occupant load anticipated (i.e., peak conditions) for different types of consumer fireworks retail sales facilities would be useful in establishing appropriate exiting provisions. Such information would help determine the number and width of exit doors, width of display aisles, etc.

8. Ignition characteristics of packaged consumer fireworks may be evaluated as a means for quantifying the flame spread hazard. Experimentally, this may be done with the use of a constant radiant external heat source and the measurement of time to ignition. Results should be consistent with the theory presented in Equation 4.

9. Once properties such as heat release rate, flame temperature and smoke composition are collected via free-burning experiments within a cone calorimeter, it is necessary to evaluate the effect of introducing water from automatic sprinklers. Information gained from the bench scale experiments with the cone calorimeter may be used as a basis for designing large scale experiments with ceiling level and/or in-rack sprinkler protection. As a first approximation, design densities (gallons per minute per unit floor area) may be estimated based upon comparison of measured data to established commodity classes.

10. Preliminary bench-scale experiments conducted by Battelle revealed that under certain conditions, as little as 5 cases of consumer fireworks (tanks, rockets, ground spinners, fountains and roman candles) produced an overwhelming fire scenario for a space equipped with an NFPA 13 wet pipe sprinkler system[47]. This result underscores the need for a deeper understanding of criteria for exempt amounts and sprinkler tradeoffs.

11. Current egress provisions for consumer fireworks retail facilities are borrowed from provisions for mercantile occupancies in NFPA 101 *Life Safety Code*. The NFPA 101 provisions are based on an established balance between occupancy type and intended use of the space, fuel loading, sprinkler protection and type of construction. The introduction of a relatively unknown commodity, from a fire protection perspective, calls the application of these provisions into question.

12. Requirements of the 2006 International Building and Fire Codes for consumer fireworks retail sale and storage facilities have no clear scientific basis. As the foundation of NFPA 1124 provisions develops, communication with the International Code Council may prove beneficial.

13. The NFPA is an international association whose stated mission is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training and education.

Currently, the scope of NFPA 1124 is limited to U.S. consumer fireworks. As knowledge of various hazards develops, it may be worthwhile to expand the scope of the standard in the spirit of this international mission.

PROJECT OBJECTIVES

The purpose of the following literature review is to assist the Fire Protection Research Foundation in developing a strong basis for enhancing fire safety standards in consumer fireworks storage and retail facilities. Pursuant to this objective, the NFPA Standards Council has identified the following list of significant topics with respect to standardization of fire protection design for these facilities.

- Safe separation distances between materials
- Requirements for passive barriers
- Separation distances to other buildings or occupancies
- Travel distance, dead end distance, occupant load requirements
- Egress capacity
- Passive egress separation requirements
- Smoke and heat venting requirements and relevance
- Alarm and detection systems including any threshold facility size
- Fire prevention strategies including ignition probability reduction and staff training
- Design requirements for sprinkler systems in retail sales facilities sensitive to the packaging and display arrangement of pyrotechnics
- Fire protection requirements for fireworks in mixed retail occupancies including big box type retail facilities

To provide a relevant context for discussion and analysis of these design issues with respect to consumer fireworks, the NFPA 1124 technical panel has specifically requested information and analysis on the following topics included in the scope of this review.

- Domestic and international fire incidents involving retail sale facilities for consumer fireworks and other incidents that may provide information on the hazard in these facilities, for example storage facility incidents or analogous commodity incidents
- Fire research and test data related to the characterization of the fire properties of materials and performance of packaging of consumer fireworks
- Hazard data / information on analogous hazard commodities
- Code provisions from other (international) codes applicable to the retail sale of consumer fireworks
- Relevant code provisions for analogous hazardous commodities in similar occupancies

As a result, the review is separated into major sections corresponding to these items preceded by a brief introduction and historical commentary. The objective of the discussion and analysis is to provide the panel with existing research data and to identify critical areas where further research is warranted to produce substantive fire protection design requirements.

INTRODUCTION

The controlled use of combustion as an engineering tool for the liberation of mass, momentum and energy is essential to civilization. Although significant technical advances over the course of history have produced more complex applications, the nature of societal dependence on combustion remains similar in many ways to the first gatherings near a flickering flame. Present day uses for this powerful tool focus primarily on the conversion of energy from its chemical form in various types of fuels to an electric potential stored and distributed for public use. Certainly one of the most common modern uses is the internal combustion engine, which captures and directly converts firepower to mechanical work. The evolution of combustion applications beyond simple heat and light was initiated by the understanding, on some level, of the intrinsic significance of chemical reactions.

Evidence of this development is found in the use of black powder mixtures in China and India as well as Greek fire on the European continent several hundred years ago. Such discoveries document the early appreciation of the ability to design and thereby control this phenomenon by manipulating the extensive properties of chemical reactants. It was precisely this enhanced control that ultimately paved the way for combustion to transition from a natural phenomenon to a catalyst for progress.

Manifestation of this progress continued in directions as significant and diverse as early advances in rocketry, mining, excavation, production of industrial materials and the invention of the steam engine. Inventions such as these held the immediate potential to transform society by generating entire industries, yet this potential would not have been fully realized without a mastery of underlying physical and chemical principles. As is often the case, this mastery came gradually as the earliest such devices operated with minimal efficiency and safety. Whether illustrated by examples of exploding locomotive steam engines, black powder manufacturing explosions or a pyrotechnic dud, the pursuit of enhanced efficiency and safety distinguish engineering by capturing this potential.

Social investment in safety is naturally driven by perceived risk. Recognition of the need for a certain degree of protection from fire is likely as old as the discovery of fire itself. The general risks associated with exposure to smoke and heat are evident when one stands in close proximity to a large flame. Perhaps in a controlled environment, methods of avoiding such risks are equally apparent. However, it is much more common in combustion applications, due to the tremendous power of this tool, that neither the potential severity of the risk source nor practical methods of avoidance are yet well understood. Such is the challenge that has faced the field of fire protection as far back as spectacular deflagrations devastating large portions of Rome, London and nearly every major city in the United States. Yet in the wake of such historic disasters, although the impetus for prevention and mitigation was well formed, the means were often primitive.

The evolution of thermochemistry and combustion physics remained separate from fire protection tradition for many years. For example, consider the fact that during the century preceding Rudolph Clausius' discovery of energy conservation (1st law of thermodynamics), colonial Boston was devastated by uncontrolled fire in the built environment on multiple occasions[1]. Although the presence of various political and economic motivations contributed to the difficulty of implementing adequate fire prevention measures, the inability to produce a rigorous engineering approach was perhaps the most significant obstacle to sustained progress[2]. (It is noteworthy that a similar obstacle existed for many black powder manufacturers forced to rely to some extent on a trial and error approach in lieu of well-established principles of chemistry[1]). It was not until the late 19th to early 20th century that a more widespread engineering approach to fire protection in the United States began to emerge. This emergence was marked by the formation of the National Fire Protection Association in 1897 in addition to various research and standardization mechanisms instituted by private insurance agencies and the federal government[3].

Although the NFPA was initially formed for the purpose of standardizing sprinkler system installation practices, the organization soon took interest in addressing fire safety issues related to explosive materials. The *Suggested Ordinance to Regulate the Manufacture, Storage, Sale, Use and Transportation of Explosives* was first issued in 1912. Also at this point in history, long-standing traditions focusing on the use of fireworks were already in existence across the globe. Celebrations such as Independence Day in the United States, Guy Fawkes Day in the United Kingdom, Bastille Day in France and the feast of San Juan in Mexico embraced pyrotechnics as an essential tool for patriotic, artistic and even religious expression in diverse cultural celebrations. These traditions formed the basis for the general use, manufacture and storage of fireworks among the general public around the world. Eventually, accidents occurring as the result of trial and error experimentation formed the general impetus for safety regulations.

Until recently, the NFPA Committee on Pyrotechnics was forbidden by the NFPA Standards Council to develop and implement fire safety provisions for consumer fireworks retail sales and storage facilities. The council reversed its position allowing for an expansion of scope in NFPA 1124 largely in response to a devastating fire incident involving a consumer fireworks retail sale facility in Scottown, Ohio in 1996. The development of fire safety provisions following such a tragedy is indicative of a pervasive loss-history-driven cycle in the field of fire protection engineering. This is a cycle that can and must be broken by a committed social investment in fire protection engineering research aimed at deepening awareness and understanding of fire risk. Without a dominating component of engineering research and development, codes and standards will stall in this loss-driven cycle.

DEFINITIONS

Perhaps the most important distinction to be made with respect to fire protection engineering objectives related to fireworks is that between consumer and display devices. As will be discussed in the following report, the general idea behind consumer fireworks is that their output is less severe than more energetic explosives, which are reserved solely for trained professional use. However, despite this generally accepted concept, the exact distinction of what constitutes a consumer firework device within the context of transportation, storage and/or use is not universal. For the sake of providing the reader with a useful initial perspective regarding this distinction, definitions currently utilized within the United States are presented in this beginning section of the report.

CONSUMER FIREWORKS are any fireworks device in a finished state, exclusive of mere ornamentation, suitable for use by the public that complies with the construction, performance, composition, and labeling requirements promulgated by the Consumer Product Safety Commission (CPSC) in Title 16, CFR, in addition to any limits and other requirements of APA Standard 87-1.[4]

Within the United States, the term is used to refer to a group of devices including ground or hand-held sparkling devices, aerial devices or audible ground devices which are specifically limited by a number of parameters, most notably to relatively small amounts of chemical (explosive and/or pyrotechnic) composition. Additional limitations include methods of packaging, overall size, specific fuse requirements, and specific requirements for reliable construction producing repeatable effects. Chemicals that are specifically prohibited for use in consumer fireworks in the United States (except as impurities < 0.25% by weight) are as follows:

- Arsenic sulfide, arsenates, or arsenites
- Boron
- Chlorates, except:
    - In colored smoke mixtures in which an equal or greater weight of sodium bicarbonate is included
    - In party poppers
    - In those small items (such as ground spinners) wherein the total powder content does not exceed 4 g of which not greater than 15% (or 600 mg) is potassium, sodium or barium chlorate
    - In firecrackers
    - In toy caps
- Gallates or gallic acid
- Magnesium (magnalium is permitted)
- Mercury salts
- Phosphorus (red or white) (red phosphorus is permissible in caps and party poppers)
- Picrates or picric acid
- Thiocyanates
- Titanium, except in particle size that does not pass through a 100-mesh sieve
- Zirconium
- Lead tetroxide (red lead oxide) and other lead compounds

In addition to these federal requirements, each state has its own laws specifically permitting and prohibiting certain devices otherwise allowed by federal regulations.

DISPLAY FIREWORKS are fireworks devices in a finished state, exclusive of mere ornamentation, primarily intended for commercial displays, which are designed to produce visible and/or audible effects by combustion, deflagration or detonation, including, but not limited to: salutes containing more than 130 mg (2 grains) of explosive composition; aerial shells containing more than 40 g of chemical composition exclusive of lift charge; and other exhibition display items that exceed the limits contained in APA Standard 87-1 for consumer fireworks.

DOMESTIC AND INTERNATIONAL FIRE INCIDENT RESEARCH

The NFPA is an international association whose stated mission is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training and education. Given this mission statement, it is clear that the international component of consumer fireworks should somehow be addressed within the scope of this effort. With respect to loss history, this task is critical because it helps form a first impression of the hazard by the reader. One of the most important points to be emphasized prior to the specifics of this analysis is that loss history resulting directly from hazards related to consumer fireworks in either the storage or retail setting is scarce worldwide. Unfortunately, this fact is often obscured by incomplete incident reports and statistics, particularly when incidents occur in non-industrialized nations. This could give the impression that consumer fireworks are to blame for any number of catastrophic incidents truly caused by significantly more dangerous explosives. For this reason, whenever possible, it is critical to analyze specific incidents beyond life loss and property damage figures to explore the root causes of the event.

Also along these lines, it is important here to address much of the existing negative publicity surrounding the use of consumer fireworks in the United States. Loss history related to consumer fireworks is dominated by personal use incidents occurring away from the setting of retail and storage facilities. According to a statistical study recently compiled by NFPA, in 2004, approximately 8,160 emergency room injuries in the United States involved fireworks permitted by Federal regulations for consumer use[5]. This number accounted for 85 percent of all emergency room fireworks injuries during that calendar year. Although this number represents a significant number of incidents related to the use of consumer fireworks, these incidents did not necessarily involve retail and storage facilities. This point regarding the relative risk of private use provides an appropriate context for the previously cited statistics within the scope of this work. In order to establish a meaningful reference for loss history corresponding to the scope of this review, it is necessary to focus on fire incidents occurring in consumer fireworks storage and retail facilities. Consequently, the remainder of this discussion focuses on the number and severity of modern domestic and international incidents with more detailed analysis reserved for high severity cases.

Tables 1A and 1B provide a list of incidents occurring within consumer fireworks storage and retail facilities. A very important distinction is made between domestic (Table 1A) and international (Table 1B) incidents specifically due to differences in both the content and enforcement of government regulations. The result is a lack of consistency in the definition of and restrictions placed upon consumer fireworks use, sale and storage. Generally speaking, the number and severity of incidents occurring domestically in storage and retail occupancies both pale in comparison to the same data on international incidents. This is undoubtedly due to the presence and perhaps also misuse of explosives that are far more energetic than those which would fit the definition of consumer fireworks in the United States.

In the past 33 years, the occurrence of a total of six domestic incidents involving the retail sale and storage of consumer fireworks is possible. However, it is important to emphasize that half of these incidents involved an unknown inventory of fireworks, which may have included consumer and display type devices as well as a number of other commodities.

There are a number of significant observations to be made from the list of domestic incidents presented in Table 1A. Perhaps the most significant is that the only known domestic casualties (deaths and injuries) associated with consumer fireworks in either the storage or retail setting occurred as the result of a single incident in Scottown, Ohio in 1996. As more detailed discussion of this event will show later in this report, this incident was also complicated by the presence of display type fireworks though the outcome was not necessarily dictated by their behavior. In addition to this observation, note that the total property loss associated with these events is quite small with the exception of the incident occurring in Missouri, which was likely exacerbated by more energetic explosives. With the exception of the Scottown, Ohio incident, the maximum known loss for a domestic facility involved in the retail sale and storage of consumer fireworks is $35,000. Lastly, all of the 3 domestic incidents known to have primarily involved consumer fireworks were initiated as the result of arson. This issue may be worth exploring in a broader context than that which is limited to overnight or seasonal lockdown. This broader context might include the proximity of untrained personnel to any pyrotechnic commodity within the facility during normal operation.

TABLE 1A. SIGNIFICANT DOMESTIC INCIDENTS [6,7]

Date	Location	Facility	Fireworks	Event	Dead	Injured
1998	Nebraska (USA)	Retail	Consumer	One-story 30 ft. x 40 ft. structure. Children broke into facility and started a trash fire. No detection. Dry pipe sprinkler system was disabled. Cardboard, wood materials stacked to ceiling height and 15 mph wind contributed to fire growth. Fire burned through roof. $35,000 total loss.	0	0
1997	Missouri (USA)	Retail and Storage	Consumer and possibly display	One-story facility, 150 ft. x 75 ft. of metal construction. No automatic detection or sprinklers. Central wall separating storage and retail burned from top down. $1 million total loss.	0	0
7/3/1996	Scottown, OH (USA)	Retail	Consumer	Customers intentionally ignited a box of fireworks inside of a single-story fireworks retail store of unprotected ordinary construction. No automatic detection system. Wet pipe sprinkler system had been disabled.	9	11
1975	Oklahoma (USA)	Retail	Consumer	Children broke into a consumer fireworks stand and set fire to facility. $1,500 property damage.	0	0
1974	North Dakota (USA)	Retail	Unknown	Child throws knife at a package of fireworks, causing ignition. Less than $1,000 damage.	0	0
1974	Oklahoma (USA)	Retail	Unknown	Fireworks stand burned down. No other details provided.	Unknown	Unknown

This limited number of known incidents over this time period implies a loss history that is quite favorable in relation to other fireworks related applications such as manufacturing and private consumer use yet this distinction is rarely made in available literature. It should be stated that although these incidents occurred over a total time span of 3 decades, activity in the consumer fireworks industry is predominantly limited to a fraction of any given calendar year. Increased activity during the peak season surrounding the July 4th or New Year's celebrations may translate to increased risk during these time periods. Although the loss history data is sparse, such a link between risk and increased activity is perhaps an area worthy of further exploration.

Disastrous incidents related to explosives are prevalent in the international community. However, the exact types and amounts of these explosives as well as the storage and handling practices utilized by the proprietors of retail shops and storage facilities are often significantly unknown. This problem is more pronounced in non-industrialized nations where government enforcement of safety regulations is weak and news reports of actual losses are often delayed and/or incomplete. Nonetheless, if one were to superficially investigate international loss history with respect to consumer fireworks, the literature would be filled with references to catastrophic events resulting in hundreds of casualties and total destruction of property. For this reason, a list of some of the most severe incidents occurring recently in the international community and loosely attributed to consumer fireworks storage and retail facilities is presented in Table 1B. General criteria for inclusion in this analysis were a relatively high number of casualties, a relatively high degree of property damage and any unique factors such as incident cause or location. Factors such as these motivate media attention to an incident, which is often most comprehensive when a significant incident occurs within a highly industrialized nation.

The single most important difference between domestic and international loss history is the commodity itself. Due to strict regulations in conjunction with proper enforcement, consumer fireworks in the United States are an altogether different commodity than the fireworks consistently made available (legally or not) to consumers in other nations. The information in Table 1B is presented in an effort to provide a tangible basis for further discussion of this issue as included in the scope of this review. In some instances, disastrous outcomes were clearly the result of highly energetic explosives, yet these tragedies were loosely attributed to consumer fireworks by media sources. The most likely reason for this discrepancy is that many such retail stores in countries such as Mexico, China or India operate under the guise of a consumer fireworks retailer while dangerous processes such as manufacturing and storage of high energy explosives are also transpiring illegally on the premises. A significant observation from Table 1B is the absence of industrialized nations where enforcement of regulations is more reliable. The type of fireworks involved in these loss incidents is generally referred to as mixed as the proportions of what would be considered consumer fireworks in the U.S. versus high energy explosives in these shops is simply uncertain. This scarcity of further information regarding specific items, particularly in light of the prevalence of under-regulated manufacturing outside the U.S., underscores the potential presence of more energetic explosives.

As denoted in Table 1B, international retail facilities are typically found in outdoor markets with very closely spaced neighboring stands. Vendors in the immediate area sell a variety of goods to people congregated in a central city location. The building planning parameters for these facilities such as type of construction, height and area and proximity to neighboring buildings are typically less regulated than their American counterparts. For this reason, such variables lack consistency between countries, particularly when juxtaposed with “big box” retail facilities found in the United States.

TABLE 1B. SELECTED INTERNATIONAL INCIDENTS[8,9, 10,11]

Date	Location	Facility	Fireworks	Event	Dead	Injured
4/5/2007	Kozhikode City (India)	Market	Firecrackers	Fire ignites within shop, spread to total of 30 nearby shops	7	> 50
11/20/2006	Guatemala City (Guatemala)	Market	Mixed	Lit cigarette set a fireworks stand on fire	15	?
9/15/2005	Tultepec (Mexico)	Market	Mixed	Fire ravages fireworks market area setting off several explosions and destroying hundreds of consumer stands. Despite warning signs against smoking, one customer purchased a single rocket, lit it and threw it into the market place.	Unknown	> 100
11/7/2000	Samut Kakkhon Province (Thailand)	Market	Mixed	Event occurred during peak season just prior to Loy Krathong festival on November 11. Explosion in shop selling fireworks in an urban area.	3	83

Although fundamental discrepancies exist between domestic and international incidents there is at least one commonality associated with risk that transcends these borders. That commonality is the human factor. It is significant that among the international incidents given the most attention by the international media, several were the result of human error. Examples include the discarding of a lit cigarette into a fireworks stand, testing of firecrackers in close proximity to a fireworks storeroom and even an incident where a lit rocket was carelessly thrown into a crowded market area containing several temporary fireworks stalls. Incidents of arson do not fall within the category of human error; as such acts are more deliberate in nature. While such incidents may be addressed by increased security measures, the factor of human error is more likely the result of inadequate training. Such training and/or public education may not be enforceable or even practical in non-industrialized nations. In such instances, other measures may be necessary to limit the interaction of untrained persons with pyrotechnic devices, particularly as the strength and sensitivity of those devices increases.

Scottown, Ohio – July 3, 1996

The single largest casualty event involving consumer fireworks storage and retail facilities in the United States occurred in the Ohio River Fireworks store in Scottown, Ohio on July 3, 1996. According to news reports, the single-story facility was roughly the size of a doublewide trailer (defined as 20 feet or more in width[12]) with exterior walls constructed of cinder block. The facility was equipped with an automatic sprinkler system; however, the system was not operational on the day of the incident. Displayed inventory on July 3, 1996 included, but was not necessarily limited to, firecrackers, bottle rockets, fountains, crackling wheels and other small fireworks including loose (unpackaged) devices[13,14]. In addition, it is known that display fireworks (then designated as Class B) were included in this inventory up to five (5) days prior to the fire event. A local arson investigator gathered evidence of these additional devices during a buy bust operation[25]. This inventory of consumer fireworks devices was displayed on either side of three (3) aisles serving the facility. This inventory included loose (unpackaged) commodity. Protective features such as flame breaks and covered fuses, which are now required by NFPA 1124, were not in use at the facility. Customers were allowed to browse freely through these aisles.

Prior to obtaining the license to sell consumer fireworks in the state of Ohio, the store was inspected by a certified safety inspector employed by the fire marshal. This inspection occurred in October 1995 and included a successful test of the store's automatic sprinkler system. The inspector noted no safety violations. However, during the previously mentioned buy bust operation, no additional inspections were performed. This is significant given that the results of an inspection in July of 1994 revealed that the sprinkler system in the store had been disabled. These circumstances preceding the tragedy underscore the utility of thorough inspections, particularly during the peak consumer season.

On July 3, 1996, the Ohio River Fireworks store contained a total of 40 customers. One of those customers, 24-year-old Todd Hall of Proctorville, Ohio, intentionally ignited a crackling wheel firework device with a lit cigarette. Very quickly, multiple fireworks became involved and building occupants rushed for the front door of the facility. Ultimately a total of nine people (one person died later of injuries sustained during the event) were killed and eleven injured as a result of the incident. All of those killed were found by investigators within five feet of the front exit[15]. The building sprinkler system did not activate at any point during the event. Investigators discovered that the system had been disabled, although one can only speculate as to the effect the system would have had on the tragic outcome. Further adding to the severity of the event was the danger posed to fire fighters by the constant discharge of fireworks within the store. For this reason, they were unable to enter the store for two hours following the initiation of the incident.

Although the most obvious inadequacy of fire protection in the Ohio River Fireworks store was the disabled sprinkler system, egress from the facility during a period of rapidly deteriorating tenability was also clearly troublesome. Witnesses of the event described a panicked crowd rushing for a single exit. Based upon published accounts of the event, it is unclear whether other exits were available or if this was simply a common decision based upon familiarity with the main entrance. In any case, the results of the inspection conducted in October 1995 indicated no safety violations, implying an exit capacity in compliance with local requirements.

Taking the above into consideration, it is important to address the factor of panic as it pertains to the traditional basis for egress provisions. Recognized experts on the topic of human behavior in response to fire in the built environment agree that true panic behavior is a rare and essentially undocumented occurrence. However, the more common occurrence of rational behavior is often attributed to limited information on the severity of the developing hazard[16]. Such was not the case during the Scottown incident in which a rapidly developing hazard within a relatively small facility prompted an equally rapid occupant reaction. Ultimately, the discovery of all victims within five feet of the exit indicates some combination of an excessive travel distance in the midst of the developing hazard and/or an insufficient exiting capacity for this particular situation. However, given that the size of this facility was approximately that of a standard doublewide trailer, the latter seems more likely to have been a limiting factor. This implies that perhaps the basis for egress design from a facility such as this should be re-evaluated.

One of the most highly regarded studies conducted on the evaluation of crowd egress focuses on the fundamental elements of time, space, information and energy of the population[17]. This research recognizes a critical pedestrian density at which shock waves are observed forming within a large crowd. The formation of a shock wave is significant because it suggests governing physics of the egress flow that differ markedly from the traditional hydraulic analogy where flow through the exit is simply the product of a constant crowd speed and density. In reality, these quantities vary in both time and space within any given egress component. Capturing these variations accurately could lead to a predictive tool for shockwave formations. In other words, conditions contributing to overloading of a particular exit path may be more accurately explored.

Tultepec, Mexico – September 15, 2005

Pyrotechnics are an integral element of Mexican culture and play an important role in the local economies of numerous towns throughout the country. Perhaps nowhere is that more apparent than in the city of Tultepec, Mexico. The city is located approximately a ½ hour drive north from Mexico City and is informally known as Mexico's capital of pyrotechnics. It is home to a population of 40,000 people as well as the most famous fireworks market and festival in Mexico. The National Pyrotechnics Fair is an annual festival officially lasting 9 days, which includes elaborate pyrotechnic displays in the form of 140-foot tall fireworks towers. On the final day of the festival, a more extreme form of celebration takes place. Hailed as "the most explosive and intimate relationship between people and fireworks on the planet", the burning of the bulls festival held on March 8 celebrates the Catholic feast day of Saint John of God (San Juan). The patron saint gained historical notoriety for rescuing several patients from a fire in the Royal Hospital of Granada in the 16th century and since has been revered as a heroic rescuer of persons endangered by fire. Local tradesmen see the festival as an opportunity to make a religious offering for divine protection from the risks related to the industry. [18,19]

Although the National Pyrotechnics Fair presents the most elaborate example of a fireworks celebration in Mexico, usage of fireworks by the general public is by no means limited to the location and duration of this spring festival. Fireworks available to consumers in Mexico such as firecrackers and skyrockets are commonly used in celebration at weddings, village celebrations and major holidays.

FIGURE 1. PREPARATION FOR NATIONAL PYROTECHNICS FESTIVAL

On September 15, 2005, the San Pablito market place included dozens of vendors. This particular incident occurred prior to the Independence Day celebration, which is a peak time of consumer fireworks usage. As a result, the market was both heavily stocked with fireworks and heavily populated with potential customers. Vendors were spread out over 300 corrugated-metal and wood temporary vending stalls within an area of approximately 4,000 square meters. The extent of the market place is unclear from media accounts of the incident, but the above figures represent the total number of stalls and area of the market that was devastated by the event (including 23 vehicles). Reportedly, a customer who had purchased a skyrocket from one of the market vendors ignored nearby warning signs against smoking and lighting of merchandise. He proceeded to light the skyrocket and throw it. The rocket landed in a nearby fireworks stand and set off a chain of explosions within the fireworks stalls. People within the market area quickly ran for safety. No deaths were reported as a result of the incident but over 100 people were treated for related injuries. It is not clear how many injuries were directly attributable to the combustion of fireworks and how many were the result of hurried egress from the market place. The exact source of the chain of explosions, which magnified the severity of an otherwise minor event, is unknown. However, given the description of the event, one could safely assume that such explosions were not the product of devices meeting criteria for UN class 1.4G fireworks or meeting the definition of U.S. consumer fireworks.

This incident in Tultepec was unfortunately one example of many that have taken place in recent years across the country of Mexico. A significant part of the safety problem is the prevalence of unlicensed manufacturing in workshops and homes. One result is a wide disparity in the explosive contents of devices sold to consumers. It is important to understand that the motivations for home manufacturing in Mexico are substantially different from those within the United States. Although there are likely some similarities in economic and personal enjoyment reasons, fireworks do not drive the economy of entire American cities, nor are they the central focus of major religious festivals. Consequently, in some Mexican cities, home manufacturing of consumer fireworks is a matter of social relevance and economic vitality. Although this may seem peripheral to the objectives of this engineering report, it is significant with respect to the implications regarding the feasibility of enforcing safety regulations. Far more deadly explosions in similar market place areas in Veracruz, Celaya, Mexico City and even Tultepec had all occurred in the recent years preceding the incident described above. However, there is no evidence that lessons were learned by the general public from these events.

Introduction for Analogous Commodity Incidents

Specifically included in the scope of this literature review is an exploration of fire incidents involving commodities (e.g., aerosol products and chemical oxidizers) which pose fire related hazards in the built environment that are in some way analogous to hazards posed by consumer fireworks. In an effort to draw useful analogies, one must address not only the burning behavior of the commodity, but also the method of storage, characteristics of the surrounding enclosure (i.e., size, fuel loading and type of construction), and the efficiency of fire protection systems. These analogies are drawn within the context of loss history recognizing that social investment in fire protection is a risk driven process.

Prior to drawing such analogies, it is important to first focus on consumer fireworks. Parameters associated with the type of facility in which this commodity is displayed, sold and/or stored vary significantly. Included in these variations are temporary showrooms that are quite common in North America. These spaces may have been originally designed for a more general purpose such as the case of an individual store in a strip-mall. In other instances, the sole purpose of the structure may be to display or store fireworks yet the temporary nature of the facility may limit the feasibility of certain fire protection methods as might be the case for automatic sprinkler protection with respect to a simple tent structure as shown in Figure 2C[20].

FIGURE 2A. RETAIL FIREWORKS IN MODULAR TRAILER

FIGURE 2B. RETAIL FIREWORKS IN STRIP-MALL

FIGURE 2C. RETAIL FIREWORKS IN MEMBRANE STRUCTURE

The images presented in the preceding figures depict structures utilized for fireworks retail. These structural descriptions are by no means exhaustive, but they do capture some of the most common types of retail applications in North America. Variations in structural fire resistance are evident. The general-purpose space within the strip-mall appears to be of ordinary construction likely with fire-resistance rated tenant separations. The modular trailer appears to be noncombustible and the membrane of the retail tent may or may not consist of a fire retardant material. This comparison implies that the significance of structural fire protection increases with proximity of the retail space to neighboring facilities. This observation may seem trivial but in fact it is important to recognize that protection of the structure is not specifically an established objective for the purpose of life or property protection within the confines of the retail space.

The protection of life and property from fire related hazards are the two principal objectives of fire protection with the protection of life taking absolute precedence. For this reason, it is important to analyze the contents of structures in terms of not only the commodity as a potential fuel but also the occupant load. The analysis must consider the potential rate of hazard development in terms of tenability within the space in relation to the total duration of egress. Also included in the broad objective of protecting the occupants of the structure is the provision of safety training to workers. Such training ideally serves to minimize the potential for human error as a source of hazard initiation. Property protection incorporates the dual objectives of achieving fire suppression or control by slowing spread and minimizing growth as well as insulating the surrounding structure from critical heat exposure. Achieving fire suppression or control with respect to any burning fuel load is dependent upon a number of factors including the type and configuration of fuel as well as the type and configuration of the suppression system. Modifications in either area may influence the efficiency of fire protection features.

The design of these particular spaces (whether indirectly by application of prescriptive requirements or directly by engineering judgement) assumed that the structural protection provided was sufficient to at least facilitate egress of the entire occupant load. This is one of the most fundamental principles of structural fire protection and it may again seem trivial that this observation is made here; however, there is a more subtle issue underlying this principle. The robustness of structural fire protection in terms of type of construction is traditionally dictated by the occupancy type or intended use of a particular space. It is in this intended use that a certain balance must be achieved between the fuel load, occupant load, size of the space and type of construction. It is this initial balance that forms the basis for the remainder of prescriptive fire protection requirements.

For example, a typical storage warehouse may occupy a large space and possess a correspondingly large fuel load, yet the fact that the occupant load is typically very small allows the focus of fire protection to ultimately shift to property protection. While this may be similar to the fireworks display tent in which access by the general public is limited to the perimeter of the structure, this balance is very different for other applications. Specifically, both the modular trailer and the strip-mall store likely possess a larger total occupant load and a more concentrated fuel loading within a smaller interior space. The impact of this proportion on necessary fire protection is likely not precisely captured by either of the traditional business, mercantile or storage occupancy classifications. More research in this area is needed; but it is also worth questioning, given the relatively low output of consumer fireworks, whether classification of such spaces as hazardous occupancies is appropriate. For a more accurate appraisal, specifics of the commodity must be explored to analyze the speed and magnitude of hazard development. Based upon this analysis, additional safety features may be required for fire suppression and/or control as well as occupant notification.

As requested by the NFPA 1124 technical panel, the following is a discussion of analogous fire-related hazards in the built environment within the context of loss history. Separate incidents relating to aerosols and oxidizers are discussed. The detail presented in the discussion is intended to clarify not only the potential similarities to consumer fireworks, but also to distinguish more clearly the differences.

Falls Township, Pennsylvania – June 21, 1982

In the past three decades, several large loss warehouse fires involving aerosol products have occurred around the globe. The four most significant incidents (in terms of total property loss) of this type occurring within the United States during this timeframe are listed in Table 2. Each of these facilities contained several types and various amounts of commodities in addition to aerosols; however, in each case, aerosols were specifically cited as contributing to the severity of the loss. The frequency of these events coupled with the tremendous property damage suffered clarified the potential benefits of both preventative and responsive fire protection design features. The loss history associated with this commodity is quite different from anything associated with consumer fireworks. As discussed in detail in the preceding section of this report, losses associated with the retail sale and storage of consumer fireworks are typically far less severe in magnitude. A rare few instances such as that which occurred in Scottown, Ohio, have proven an exception to the rule. It is important to present the loss history of aerosols here because it helps build the proper perspective for evaluating the necessity and practicality of certain fire protection design requirements for a given application.

TABLE 2. LARGE LOSS AEROSOL FIRES IN THE UNITED STATES[21]

Year	Location	Facility	Storage Area	Storage Configuration	Property Damage
1979	Edison, NJ	Supermarket General	290,000 ft^2	Rack	\$30M
1982	Falls Township, PA	K-Mart Distribution Center	1,200,000 ft^2	Rack, palletized	>\$100M
1985	Elizabeth, NJ	MTM (Mitsui)	500,000 ft^2	Rack	\$150M
1987	Dayton, OH	Sherwin-Williams	180,000 ft^2	Rack, palletized	\$49M

Perhaps the incident most formative for fire protection codes and standards related to aerosols occurred in the *K Mart* distribution center and warehouse facility in Falls Township, Pennsylvania. This facility was a one-story, 1.2 million square foot structure of unprotected noncombustible construction on a concrete slab. The roof of the facility was designated as a Class I steel deck as defined by the 1980 edition of NFPA 203M *Manual on Roof Coverings and Deck Constructions*. Exterior walls were built of a combination of poured concrete below insulated metal panels. The warehouse was subdivided by interior fire walls into quadrants[22].

Commodities stored within the warehouse were diverse in type and large in quantity. A total of approximately 15,000 different products spanning all categories of commodity classifications (1980 edition of NFPA 231C *Standard for Rack Storage of Materials*) were stored throughout the space. Among the most hazardous materials were a variety of plastics, aerosols and rubber tires. The method of storage was fairly consistent with roughly equal portions of floor space devoted to commodities either on pallets or in single-and double-row racks with a maximum height of 15 feet. The maximum length of storage racks was in excess of 300 feet. [23]

A hydraulically designed wet pipe sprinkler system was provided throughout the facility with a design density of 0.40 gpm per square foot to be delivered over the most remote 3,000 square feet. All sprinklers were located at ceiling level. Each was a standard spray upright (SSU) with an operating temperature of 286°F and an orifice of 17/32 inch[24]. A proprietary fire alarm system was designed to provide supervision of the sprinkler system. Alarms were transmitted both visually and audibly to a constantly attended on-site location. Guards at these locations were trained in emergency response procedures. In addition to this system, smoke and heat vents were provided throughout the facility at an area ratio of 1:96 (vent area to floor area)[24].

The events of June 21, 1982 began at approximately 12:30 PM when the operator of an electrically powered lift-truck selecting products accidentally knocked over a carton of carburetor and choke cleaner from its palletized storage location. The resulting fire spread so quickly through adjacent commodities that by the time the employee had returned with a nearby fire extinguisher, the blaze was beyond his capabilities to control. Witnesses estimated that the entire volume of Quadrant B filled with smoke within 3 minutes following ignition. This situation in which the rate of hazard development overtaxed provisions for personnel response is certainly analogous to the events in Scottown, Ohio and may be a more general similarity between these commodities if proper prevention measures are not in place. This implies that effective safety training should focus primarily on prevention as opposed to response.

Perhaps the most significant observation throughout the fire event was made by fire department personnel inside the facility who witnessed what they referred to as exploding aerosol cans rocketing in several directions with trails of flaming contents. These directions included directly through the deluge water curtains intended for fire wall opening protection as well as through the roof. This phenomenon undoubtedly contributed to the spread of fire from within Quadrant B to the remainder of the facility as well as the roof covering. Additionally, due in part to the added danger of exploding projectiles within the building, the fire department was forced to focus on exterior attack methods[23].

According to the official investigation of the *K Mart* distribution center fire loss conducted by NFPA, all fire protection equipment was thought to have functioned properly during the fire. Additionally, the actions of the fire department in response to the event were reviewed by investigators and deemed appropriate. The investigators concluded that the following deficiencies were chiefly responsible for this catastrophic failure[22]:

1. The automatic sprinkler system was not specifically designed to control the fire hazard resulting from the storage of large amounts of petroleum-liquid-based aerosol products.

2. Commodities were not isolated according to the level of fire hazard. Particularly hazardous products such as aerosols were intermingled with various types of merchandise throughout the entire warehouse. This allowed for other perhaps more hazardous commodities to contribute to the outcome of the event.

3. The fire walls separating the facility into quadrants were designed with insufficient opening protection in the form of water curtains. These water curtains did not prevent the spread of fire via flaming aerosol projectiles on either side of the barrier.

In general purpose strip-mall stores used for retail sales of consumer fireworks, providing adequate fire protection features (i.e., sufficient water flow and distribution from automatic sprinklers), is similarly an important issue. The *K Mart* distribution center fire provided the fire protection community with evidence of the need for focused sprinkler protection on this particular commodity. Subsequent experimentation by Factory Mutual Research and the aerosol industry eventually led to the modern design approach, which recognizes that fire severity is primarily dependent on the overall heat of combustion of the aerosol can contents[21]. Consequently, characteristics of water flow from automatic sprinklers designed to protect aerosols are now governed in part by the heat of combustion of the commodity. A similar distinction may or may not be present for various packaged consumer fireworks relative to ordinary combustibles. The importance of the heat of combustion of the commodity on determining an appropriate level automatic sprinkler protection underscores the need to experimentally evaluate the heat of combustion of packaged consumer fireworks. Such information could also be compared to the heat of combustion of unpackaged devices in order to quantify the relative influence of packaging.

The projectile hazard presented by this commodity is the most significant similarity to fire hazards associated with consumer fireworks. The thermal component of this hazard is found in the potential for fire spread to otherwise uninvolved commodities. Additionally, the mechanical component of this hazard is clearly the impact of projectiles on either building occupants or responding firefighters. It should be noted that only some consumer fireworks are designed to exhibit projectile behavior (most are sparkler, fountain-type devices).

As a projectile, aerosols exhibit both a mechanical impact hazard and a thermal fire spread hazard due to a trail of flaming contents. Both impact and thermal hazards are relevant to consumer fireworks though perhaps less pronounced in these generally smaller objects. The mechanical hazard posed by a projectile is dependent on its momentum, which is a product of its mass and velocity. Although data comparing the peak velocity of consumer fireworks designed as projectiles versus burning aerosol cans was not found by this author, the mass of a typical can of aerosol is expected to be characteristically larger than a projectile consumer firework device (i.e., bottle rocket). Differences in the severity of the projectile hazard are therefore expected (assuming similar velocities). Nonetheless, the concept of containing projectiles remains an important similarity for fire safety. Due credit is given to the 2006 edition of NFPA 1124 which contains requirements for restraining aerial devices on display with packaging that limits the projectile hazard (Section 7.3.15.6). This may be accomplished by methods including packaging fireworks in bins or other structures as well as fastening devices together.

The lesson of commodity segregation demonstrated by the importance of fire barrier walls in the *K Mart* distribution center fire is also germane to consumer fireworks. The useful analogy here would be between the fire barrier wall in the warehouse and the flame break within a display unit. The goal of the passive fire barrier in the distribution center was to contain the fire to one side of the wall for its entire duration. As a result, the wall needed to maintain its structural integrity under high thermal exposure. For flame breaks used in consumer fireworks display racks, the goal is to provide containment of heat for a certain time period. Determination of the appropriate time period in the warehouse was based upon potential property loss as the time necessary to protect property far exceeded the time necessary to provide egress.

For thermally and structurally isolated consumer fireworks sales and storage facilities often the only time scale of importance is associated with complete evacuation and property protection is simply not a concern. Despite the differences in these time scales, both fire walls and flame breaks are barriers designed to limit the passage of heat over a finite period of time. Consequently, properties of the material that govern heat absorption (i.e., thickness, density, specific heat and thermal conductivity) are critical design variables. Universally, building codes and standards solve this design challenge for fire barriers indirectly by measuring the duration (i.e., 1-hour, 2-hours, etc.) over which a wall section maintains its structural and thermal integrity when exposed to a standard heat exposure (i.e., a furnace calibrated to a specific maximum and rate of rise of temperature).

To approach this design issue in a similar manner for flame breaks used in consumer fireworks display racks, a standard heat source would first need to be defined. As a first approximation, the adiabatic flame temperature presented later in this report (Equation 2) could be used or a value could be measured experimentally for free-burning packaged fireworks. The flame break could then be designed to resist one-dimensional steady state heat transfer by increasing the ratio of thickness to thermal conductivity[25]. In other words, a thick sheet of steel would be more durable for this purpose than a thin sheet of aluminum because of this property ratio. Structural dependence of the flame break on the display rack must also be addressed, as this was a key issue with respect to the failure of fire barriers in the *K Mart* distribution center. If the flame break is not structurally independent of the rack, deformation of the rack upon heating may compromise the efficiency of the flame break.

Phoenix, Arizona – August 2, 2000

The term oxidizer possesses multiple connotations and as a result it is necessary to qualify the context of its use with respect to fire protection engineering. With relation to fire protection, NFPA 430 *Code for the Storage of Liquid and Solid Oxidizers* defines an oxidizer as "any material that readily yields oxygen or other oxidizing gas, or that readily reacts to promote or initiate combustion of combustible materials and can undergo a vigorous self-sustained decomposition due to contamination or heat exposure."[26] In other words, although oxidizers may not necessarily be combustible in and of themselves, their hazard lies in the ability to increase the fire severity of surrounding materials. This increased severity may be in the form of a more rapid burning rate of combustible materials, higher flame temperatures, spontaneous combustion or thermal decomposition.

Similar to aerosols, the historical losses associated with oxidizers are far more severe than anything associated with consumer fireworks. This characteristic difference in loss history is likely the product of how these commodities are defined. In other words, consumer fireworks are specifically defined with the objective of excluding all but the least hazardous types of devices. Conversely, oxidizers include a wide range and large number of products of varying use and hazard severity. For this reason, oxidizers as a whole are produced and stored in larger quantities than consumer fireworks. These issues contribute directly to the characteristic distinction in loss history between these commodities.

One of the most significant similarities between oxidizers and consumer fireworks lies in the independence of the rate of hazard development on the ventilation of the fire enclosure. The commodity itself provides the necessary oxidizer to sustain combustion in the presence of limited ventilation. This similarity is significant from the perspective of fire suppression/control, which is founded on the concept of the fire tetrahedron. This essentially refers to the four essential factors for sustaining combustion, which are fuel, oxidizer, heat and an uninhibited chain reaction[27]. Removal of any of these factors from the process, in sufficient quantity, yields control and/or suppression. Both oxidizers and consumer fireworks contain prepackaged fuel and/or oxidizer. Therefore, removing either of these elements from the reaction zone is impractical.

Additionally, exploring the use of a special hazard suppression system utilizing a chemical agent to inhibit the combustion reaction would be complex with associated costs likely not justified by relevant loss history. The most practical means for achieving fire control and/or suppression is the removal of heat from the reaction zone. This is most effectively and practically accomplished by the application of water, which possesses a high specific heat (characteristic property of high heat absorption). In an effort to increase the efficiency of water application, factors such as early activation (ESFR) and manipulation of characteristic droplet size and distribution are worthy of exploration.

Note that existing requirements for retail storage of oxidizers include in-rack sprinkler protection to provide adequate water access and a combination of horizontal barriers in every tier with vertical barriers at all rack uprights to confine fire spread. NFPA 1124 is currently interested in the confinement of fires related to consumer fireworks with the use of flame breaks as well as the determination of appropriate sprinkler protection criteria. While the exact methods employed for the protection of oxidizers may or may not be necessary for consumer fireworks, it is useful to note that oxidizers are divided into hazard classes based essentially upon their heat generation potential (i.e., burning rate, reaction temperature). This potential certainly is affected by net quantities, which are characteristically larger than oxidizers contained in packaged consumer fireworks. Nonetheless, it is important to note the logical trend in protection, which calls for increased design densities from automatic sprinklers and increased robustness of passive fire barriers as the class of the oxidizer increases. This emphasizes the need for evaluating factors such as the reaction temperature and burning rate of packaged consumer fireworks.

These issues are perhaps most clearly illustrated in one of the largest fire loss events related to oxidizers, which occurred recently in a single-story (approximately 30 ft ceiling height) multi-tenanted storage warehouse in Phoenix, Arizona in 2000. The southern half of the approximately 80,000-ft^2 warehouse was occupied by a Home and Garden supply store with a Pharmaceutical facility occupying the remaining northern area. The areas were separated by a concrete panel wall. The only significant openings around the perimeter of the building were a series of overhead doors along the east exterior wall. The roof of the facility was constructed of plywood decking covered by layers of asphalt supported by wooden rafters on steel columns. Storage within the warehouse included products typical of a home and garden supply store such as lawn and garden care products, oxidizer-containing pool care products, landscaping materials, artificial fireplace logs, hand tools, lawnmower accessories and wood planters with clay pots[28]. Methods of storage included solid and open shelf rack storage over 20 feet in height in both single and double-row racks with 8 – 10 foot wide aisles. Several commodities were also stored on pallets in solid pile arrangements at maximum heights of approximately 10-12 feet. Some of these pallets were partially encapsulated in plastic sheathing. Additionally, some materials were stored in corrugated cartons.

Fire protection systems in the warehouse included an automatic sprinkler system with coverage throughout the facility. The design density for the Home and Garden center was 0.495 gpm over a remote area of 2,000 square feet. Sprinklers possessed a 286°F temperature rating and an orifice of 17/32 inch with a k factor of 8.0. The hydraulic demand for the Home and Garden area was 1,530.1 gpm at 56.3 psi pressure[28]. Specifics of the sprinkler system design are provided here as a reference for fire protection professionals to illustrate that sprinkler protection was designed in accordance with a standard approach for Class IV commodities.

At approximately 5:00 pm on August 2, 2000, less than an hour after the close of business for the Home and Garden warehouse, plumes of smoke were observed rising from the southern area of the facility. Early observations of white smoke coinciding with banging noises therefore suggest that pool chemicals were among the first materials to undergo the process of combustion during this fire event[29]. Subsequent explosions heard by the fire department may have disrupted the storage configuration of these chemicals thereby granting more substantial access for water being discharged by the sprinkler system. However, by this time, fire had likely spread to many commodities throughout the facility. Shortly thereafter, the fire department reported several spot fires in the outside storage area. Ultimately, following the collapse of the interior concrete wall separating the building tenants, the entire building was destroyed by fire.

No deaths occurred as a result of the incident and the only injuries were related to firefighting operations.

The most significant lessons learned from this fire event were quite similar to those of the *K Mart* distribution center fire. Segregation of materials on the basis of fire related hazards might have reduced the rapidity of fire spread from the oxidizers in the initial stages to surrounding hydrocarbon fuels. Additionally, the automatic sprinkler system in the warehouse was not designed to adequately protect the fuel load within the space[28]. Rather, the system was designed to provide a rate of heat absorption that did not correspond to the rate of heat generation of the commodity in the warehouse. The lack of occupants within the structure at the time of the event certainly contributed to the absence of casualties. It is assumed that the speed of hazard development could well have exceeded the response capabilities of personnel. As a result, a focus on prevention during safety training seems appropriate.

Loss History Conclusion

Loss history related to consumer fireworks is dominated by personal use incidents occurring away from the setting of retail and storage facilities. Documented fire losses related to the retail sale or storage of fireworks meeting the definition of consumer fireworks provided in NFPA 1124 is scarce worldwide. The only known domestic casualties (deaths and injuries) associated with this commodity in either of these applications occurred as the result of a single incident in Scottown, Ohio in 1996.

The inventory of fireworks in this facility included some display type fireworks, though the contribution of these more energetic devices to the final outcome of the event is only a matter of speculation. It is also important to note that this inventory included some loose (unpackaged) commodity. Protective features such as flame breaks and covered fuses, which are now required by NFPA 1124, were not in use at the facility at the time of the fire. Although the most obvious inadequacy of fire protection in the Ohio River Fireworks store was the disabled sprinkler system, egress from the facility during a period of rapidly deteriorating tenability was also clearly troublesome.

A significant safety problem related to fireworks in the international community is the prevalence of unlicensed manufacturing in workshops and homes. One result is a wide disparity in the explosive contents of devices sold to consumers. Consequently, although detailed information regarding international fire losses is difficult to find, many such incidents purportedly involve fireworks and result in large explosions. It is critical to recognize that such a violent outcome is indicative of the presence of high-energy explosives, which do not meet the NFPA 1124 definition of consumer fireworks (or any other known definition).

Based largely on accounts of the fatal fire in Scottown, Ohio, fire hazards related to consumer fireworks in the built environment most notably include the presence of prepackaged fuel and oxidizer within the commodity leading to a characteristically high rate of heat production, a potential for rapid deterioration in tenability due to products of combustion and projectile behavior of aerial devices. Due credit is given to the 2006 edition of NFPA 1124 which contains requirements for restraining aerial devices on display with packaging that limits the projectile hazard (Section 7.3.15.6).

The characteristically high rate of heat generation is a fire behavior, which is generally analogous to oxidizers. Established fire protection strategies for this commodity focus on the removal of heat from the reaction zone. This is most effectively and practically accomplished by the early application of water combined with the confinement of the fire to a design area bounded by both vertical and horizontal fire barriers. As the expected rate of heat generation increases, so should the design rate of water application and the robustness of fire barriers. For oxidizers, the anticipated hazard level is quantified in terms of the heat of combustion, which is a measurable quantity for packaged consumer fireworks. Comparison of such measurements to existing data for oxidizers may be a useful step toward quantifying the relative commodity hazard. When the relative hazard is quantified, appropriate rates of water application and methods of fire confinement may be more thoroughly explored. In the design of flame breaks, properties of the material that govern heat absorption (i.e., thickness, density, specific heat and thermal conductivity) are critical design variables.

The rate of generation as well as the composition of combustion products is another important hazard that must be addressed by future research. Intuitively, as fire growth and spread is brought under control by passive confinement and the application of water, the rate of generation will also be slowed. However, specific data regarding the composition of combustion products and their respective toxicity is important.

Lastly, all of the domestic incidents documented in this report were initiated by arson and in some cases the outcome was exacerbated by negligence (i.e., disabled sprinkler system). This supports an increased focus on inspection, security and safety training of personnel, which is reflected in current NFPA 1124 requirements. NFPA 1124 did not exist at the time of these incidents. Had it served as a basis for rigorous inspections of the Scottown facility prior to July 3, 1996, this defining event might have been mitigated.

FIRE RESEARCH AND TEST DATA

The effectiveness of implementing current NFPA 1124 provisions in the Ohio River Fireworks store prior to the events of July 3, 1996 is unfortunately a matter of speculation. Logically, various increases in the level of fire safety could well have lessened the severity of the fire. It is important to question whether proper packaging of consumer fireworks with features including covered fuses and flame breaks may have slowed flame spread and provided critical time for continued egress from the facility. However, without the support of scientific theory and/or experimental data, the efficiency of such features intended to mitigate similar events remains a question unanswered.

The intent of this literature review is to identify and analyze existing research throughout the scientific community that contributes to building a foundation for fire safety in consumer fireworks storage and retail sales facilities. The following survey and analysis of research and test data is deliberately separated into pyrotechnic and fire protection sections. The reason for this separation is that fire protection research traditionally focuses on the full-scale complexity of hazards involving not only the combustion process but also the role of various mitigating features in the system. In contrast, the literature on pyrotechnics focuses specifically on the physical and chemical processes taking place within the combustion source. It is precisely this understanding of the combustion source that provides the necessary context for the more global perspective of the fire protection engineer. In other words, it is the behavior of the fire source that dictates appropriate and effective methods of fire protection.

Fire in the built environment is hazardous to life and property because of the generation and dispersion of heat and chemical compounds, which are incompatible with the intended use of the space. Fire protection engineering therefore approaches the objective of the protection of life and property from fire related hazards by analyzing the generation and dispersion of heat and chemical compounds. Ideally, such an engineering approach is rooted in scientific theory and validated by experimental measurements. The following is a discussion of existing scientific theory related to the generation of heat and chemical compounds. The discussion focuses on the enthalpy of combustion, reaction temperature, reaction rate and generation of products. The intent of this discussion is to identify methods of quantifying these basic but significant parameters so that a basis for protection strategies may be formulated. For instance, features such as flame breaks and packaging provide insulation from heat exposure. Optimization of the insulating qualities of these features logically requires knowledge of the magnitude of the heat exposure (i.e., flame temperature, rate of reaction, etc.).

Enthalpy of Combustion

The enthalpy of combustion is a measure of the total heat evolved, whether released or absorbed, as the result of a complete combustion reaction. Combustion is a complex phenomenon, which often involves numerous initiating, chain-branching and chain-terminating steps in any given chemical mechanism. Fortunately, according to Hess' law, the enthalpy of combustion is dependent only on the initial and final states of the system (Equation 1). In other words, this value is independent of the often-complex pathway taken as the chemical reactants are converted to products[30]. This relationship is expressed mathematically in Equation 1. It is important to note that the enthalpies of both the products and reactants are temperature dependent.

$$\Delta H_{combustion} = H_{products} - H_{reac\tan ts} \tag{1}$$

Where:

$\Delta H_{combustion}$ = Heat of combustion [J]

$H_{products}$ = Heat of formation of products [J]

$H_{reac\tan ts}$ = Heat of formation of reactants [J]

In addition to the general calculation method presented above, the heat of combustion for any given pyrotechnic composition may be determined experimentally via a bomb calorimeter. Such measurements could be taken for packaged or unpackaged consumer fireworks. Comparison to the heat of combustion of materials with established automatic sprinkler protection criteria (i.e., varying commodity classes) may be worthwhile for estimating appropriate sprinkler design criteria.

Reaction Temperature

Determining the maximum temperature of the combustion reaction is particularly important with regard to fire protection objectives. It is this temperature that governs the amount of heat lost from the reaction zone to its immediate surroundings. This estimated heat loss often dictates the design of separation distances and/or the heat capacity of passive thermal barriers such as flame breaks or elements of packaging designed to insulate the commodity (i.e., covered fuses).

The temperature field of the reaction zone fluctuates in both space and time. The exact temperature at any given instant and location within a flame is often governed by complex phenomena including turbulent flow and molecular diffusion. However, an estimation of the maximum temperature may be conservatively made with knowledge of both the heat of combustion and the heat capacity of the chemical constituents in the reaction (Equation 2). The result is a quantity known as the adiabatic flame temperature. The term adiabatic is used to qualify the significant assumption that the reaction does not lose any heat to its surroundings, nor is the temperature decreased by thermal dissociation. In reality, both of these modes of heat loss are expected. The result is an overestimation of the maximum temperature, which may be viewed as conservative from a safety standpoint. Depending on the conditions of the system, this calculation may be made to account for combustion occurring at either constant pressure or constant volume. This calculation method is thought to be sufficiently accurate up to temperatures of 2500°C. The temperature of most pyrotechnic mixtures falls within a 2000°C – 3000°C range[31]. This range is significantly higher than expected adiabatic temperatures for ordinary combustibles, thereby underscoring the need for heat removal from the reaction zone as a means of fire control/suppression (analogy to oxidizers).

$$T = \frac{Q - \sum(Q_S + Q_K)}{\sum C_{p,v}} \tag{2}$$

Where:

$T =$ Reaction temperature [°C]

$Q =$ Heat of combustion [cal]

$Q_S =$ Heat of fusion [cal]

$Q_K =$ Heat of vaporization [cal]

$C_{p,v} =$ Specific heat (constant pressure, constant volume) [cal/°C]

A number of experimental methods are also available for obtaining more accurate estimates of the reaction temperature. These methods include measurements and analysis of radiation intensity based upon optical wavelength[31].

Reaction Rate and Flame Spread

The rate of reaction is the engine that powers combustion. For a pyrotechnic composition, the rate is governed by a combination of chemical influences and physical conditions. The entire pathway or mechanism of a combustion reaction often includes numerous steps, which may be simplified for the purposes of estimating total heat evolved; however, they must be considered in detail when estimating the reaction rate. Although modern methods of modeling chemical kinetics are available for conducting specific analyses[32], existing analytical data in this area of pyrotechnics research is sparse. Significant complexities of the physical system include the effects of ambient pressure and the phenomenon of pulsating combustion. Each of these influences upon heat transfer processes within the reaction zone may require further study.

Heterogeneous combustion categorizes a type of reaction incorporating chemical species in both condensed and gaseous states. These types of reactions are fundamentally different from homogeneous reactions in which the mechanism for combustion is the collision of gaseous molecules. The combustion of pyrotechnic compounds differs fundamentally from that of explosives in that the former occurs as a heterogeneous reaction process. This type of reaction includes numerous complexities that must be addressed to achieve precise rate estimates. For instance, in situations where powders and explosives are confined, the evolution of copious amounts of gaseous combustion products can significantly increase the pressure within the fixed volume. The reaction rate is consequently increased as the higher pressures increase heat transfer from the flame to the fuel. The opposite is true with decreasing pressure. Below critical values, combustion is not sustained. The effect of external pressure on the rate of reaction is expressed in terms of a correlation in where constants are dependent primarily upon the type of fuel and the range of external pressure[31].

$$\dot{m} = C_1 + C_2 P \tag{3}$$

Where:

$\dot{m} =$ Reaction rate [g/cm^{2}s]
$C_1, C_2 =$ Empirical constants
$P =$ System pressure [kg/cm^2]

Due to the complexity of producing theoretical estimates of the burning rate of complex materials, efforts to quantify this parameter typically consist of experimental measurements of the rate of mass loss of a burning fuel. The result is the indirect quantification of the reaction rate given knowledge of the rate of conversion of solid reactants to gaseous products. The mathematical product of the mass loss rate and the heat of combustion of the fuel provides an approximation of the rate of heat generated by the global reaction.

Many parameters associated with arrangement of commodity in storage and/or display configurations can influence the rate of heat generation synergistically. Research conducted on factors related to rack storage of ordinary combustibles and also for plastic commodities concluded that the magnitude of the heat release rate is proportional to the number of tiers of storage during the early stages of fire development (the timeframe during which activation of ESFR sprinklers would be expected)[21]. Flue space and aisle width have also been found to be influential for fire growth and spread when dealing with ordinary combustibles. For this type of fuel, separation of the burning fuel from adjacent commodity governs not only the magnitude of radiant heat exchange but also the access of ventilation that is critical to the combustion process. However, the latter of these effects (ventilation) is not important in the same way for consumer fireworks, which are equipped with a prepackaged supply of fuel and oxidizer. Still, fire spread to packaged fireworks will be governed partly by the ignition of typical packaging materials for the fireworks (i.e., 4G corrugated cardboard boxes). Flame spread to packaging materials may be quantified by experimental measurements of ignition under an imposed external radiant heat flux (ASTM E 1321 or ASTM E 1354 are established standardized methods). For thermally thick materials, ignition time may be estimated as shown in Equation 4[2].

$$t_{ig} = \frac{\pi}{4} k\rho c \frac{\left(T_{ig} - T_{\infty}\right)^2}{\dot{q}_e''^2} \tag{4}$$

Where:

$t_{ig} =$ Exposure time required for ignition at constant heat flux [s]
$k =$ Thermal conductivity [W/mK]
$\rho =$ Density [kg/m^3]
$c =$ Specific heat [J/gK]
$T_{ig} =$ Ignition temperature of material [K]
$T_{\infty} =$ Ambient temperature [K]
$\dot{q}_e'' =$ External heat flux [W/m^2]

The theory presented in Equation 4 provides some additional insight into the use of packaging as a tool for slowing flame spread. According to this equation, an increase in the density of a material corresponds to a proportional increased in the time required to reach its ignition temperature. Therefore, a practical means for slowing fire spread through racks of packaged consumer fireworks might be to store the fireworks in boxes comprised of a higher density material than corrugated cardboard. Note that an appropriate external heat flux could be calculated from knowledge of the flame temperature and/or heat release rate of the commodity.

Composition of Reaction Products – Issues of Tenability

The evolution of combustion products is of course important to the design of pyrotechnic mixtures; however, it also carries particular significance for fire protection in terms of the resulting tenability of the surrounding environment. Fire protection engineers performing design calculations for smoke production often assume diffusive burning of fuel and oxidizer producing an axisymmetric (symmetric entrainment of air about an axis through the centerline of the fire) fire plume. Smoke production is therefore estimated primarily as a function of the entrainment height of the rising plume with a less significant influence from the rate of reaction.

The assumptions inherent to the correlations used in such design calculations do not necessarily apply to packaged consumer fireworks wherein the mechanism for smoke production by the pyrotechnic composition differs from that of the burning packaging.

If the volume of the composition is known, the Gay-Lussac formula may be used to estimate the volume of gaseous products resulting from combustion of a pyrotechnic mixture (Equation 5A). This quantification of the amount of products may be helpful in classifying relative hazards with respect to general visibility[31]. This method of estimation may also be useful in determining the necessity for smoke extraction from a retail facility based upon the total amount of products expected to be produced during a design fire scenario. The specific volume of products at standard temperature and pressure may either be calculated as shown in Equation 5B or experimentally determined.

$$v_T = v_o(1+0.00366T) \tag{5A}$$

Where:

v_T = Specific volume of products at reaction temperature [cm^3/g]
v_o = Specific volume of products at 0^oC and 760 mm Hg [cm^3/g]
T = Temperature of the reaction [^oC]

$$v_o = 22{,}400\frac{n}{m} \tag{5B}$$

Where:

n = Sum of product coefficients [number of gram-moles]
m = Mass of the reactants [g]

Experimental measurements of smoke production and composition from burning packaged consumer fireworks may be acquired through the use of a cone calorimeter. Such data would be necessary to confirm the validity of existing correlations or to introduce a commodity specific approach.

Ultimately, for purposes of estimating transient visibility conditions within a system polluted by these products, it is necessary to establish the rate at which they are being produced by the reaction and estimate based upon the chemical yield of each constituent. This rate of production may then be used as the basis for determining a necessary rate of extraction from the space.

The most authoritative data in the fire protection engineering community on the topic of visibility through smoke was collected during a series of experiments conducted by Jin[33]. In addition to developing correlations for estimating visibility in fire smoke, this study examines issues related to human behavior, which are significant with respect to egress as observed in the Scottown, Ohio incident. The correlations developed by Jin to estimate visibility as a function of light scattering and smoke density should apply fairly well to consumer fireworks related occupancies. However, it is important to note that some consumer fireworks produce colored smoke, which was not examined in these tests. This colored smoke may significantly alter factors such as the contrast threshold, which are critical to the applicability of these correlations.

The issue of smoke composition is perhaps more troublesome as consumer fireworks contain a number of chemical compounds which may produce levels of eye irritation and general toxicity which vary markedly from fires in other retail and storage occupancies. Jin's research illustrated quite clearly that visibility and walking speed decline steeply at a critical extinction coefficient of 0.5 m^{-1}. The comprehensive effect of such a sharp decrease visibility on human behavior is not yet thoroughly understood. Unfortunately, the same can be said for the assessment of toxicity of products of combustion evolved from consumer fireworks. Generally, toxicity is evaluated in terms of a fractional effective dose which is a ratio of the cumulative dose received to the effective dose required to cause incapacitation or death[34]. Therefore, in order to evaluate tenability, the chemical composition of the source must be known. A list of chemicals commonly used in pyrotechnic compositions is listed in Table 3[35]. Note that some of these chemicals are severely limited in quantity for consumer fireworks in the United States (i.e., chlorates).

Some additional data is available in the form of a recent chemical analysis of Swedish consumer fireworks, although this work was performed with respect to solid-state pyrotechnic composition as opposed to products of combustion[36]. Certainly among the most dangerous elements analyzed in the study were arsenic, cadmium, lead and mercury, on which the study specifically focused. However, it is significant that such chemicals are specifically prohibited for use in U.S. consumer fireworks. In addition, the size of cakes and shells in particular far exceed what would be domestically classified as consumer fireworks (i.e., 95 mm shell in mortars) although data is presented on a mass fraction basis. This lack of uniformity is problematic if the objective of NFPA 1124 is to provide universally applicable fire protection design strategies. Although this specific data may not be directly applicable to an analysis of U.S. consumer fireworks, it is presented here as an example of the type of data needed as a basis for analyzing tenability.

TABLE 3. COMMONLY USED FIREWORKS CHEMICALS

Chemical / Substance	Function
Potassium Nitrate	Oxidizer
Potassium Perchlorate	Oxidizer
Potassium Chlorate	Oxidizer
Ammonium Perchlorate	Oxidizer
Barium Nitrate	Oxidizer, Colored Flames
Barium Chlorate	Oxidizer
Strontium Nitrate	Oxidizer, Colored Flames
Aluminum	Fuel
Magnalium	Fuel
Titanium	Fuel
Charcoal	Fuel
Sulphur	Fuel
Dextrine	Fuel, Binder
Red Gum	Fuel
Antimony Sulfide	Fuel
Iron Filings	Sparks
Coarse Charcoal	Sparks
Flake Aluminum	Sparks
Strontium Carbonate	Colored Flames
Barium Carbonate	Colored Flames
Copper Oxide	Colored Flames
Copper Carbonate	Colored Flames
Sodium Oxalate	Colored Flames
Cryolite	Colored Flames
Rice Starch	Binder
Shellac	Binder

The data presented from the Swedish analysis was taken with respect to solid-state pyrotechnic composition as opposed to the measurement of products of combustion. Knowledge of the latter is critical to assessing tenability within a room as a result of a developing fire. Although the Swedish data could potentially be used to estimate chemical yields as a result of combustion in certain scenarios, such estimates would still require comparison to experimental data for validation purposes.

Regulation of combustion product toxicity for pyrotechnic materials was explored recently by French and Canadian researchers who identified principle reasons for a general absence of regulatory control in the international community[37]. Reasons relevant to consumer fireworks included the dependence of product composition on the fire scenario as well as the general absence of loss history regarding acute or sub-acute exposure. The fatal fire in Scottown, Ohio is certainly an exception to this rule. The location of several fire victims in close proximity to exits is an indication of a rapid deterioration of tenability within the room of origin; however, the author of this literature review was unable to obtain specific toxicity information for this incident.

TABLE 4. SWEDISH CONSUMER FIREWORKS CHEMICAL ANALYSIS*

Element	7 rockets (5 types) [g/kg]	7 rockets (4 types) + 2 mini cakes [g/kg]	25-shot cake [g/kg]	25-shot cake [g/kg]	52-shot cake [g/kg]	95 mm shell in mortar	Mean [g/kg]
Aluminum	36	32	59	54	64	43	48
Arsenic	0.0024	0.044	0.013	0.01	0.046	0.003	0.02
Barium	38	12	26	51	37	72	39
Boron	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Cadmium	0.0032	0.02	0.0037	0.0044	0.021	0.0035	0.0093
Calcium	2.4	3.4	0.85	0.72	0.88	0.57	1.5
Chromium	0.028	0.95	0.0076	0.0078	0.5	0.0068	0.25
Cobalt	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003
Copper	10.9	0.75	23	10.4	0.77	0.31	7.7
Iron	1.3	9.2	0.58	0.57	0.25	1.4	2.2
Lead	46	3.2	6.8	2.5	5.3	0.037	11
Magnesium	21	22	27	30	32	42	29
Manganese	0.23	0.5	0.099	0.11	0.25	0.12	0.22
Mercury	0.00032	0.00044	0.00019	0.00027	0.00051	0.00018	0.00032
Nickel	0.012	0.808	0.0086	0.0082	0.02	0.036	0.15
Phosphorus	< 0.10	< 0.10	0.16	< 0.10	< 0.10	< 0.10	< 0.11
Potassium	160	190	170	160	180	140	167
Strontium	3.2	0.056	9.7	0.096	3.8	0.34	2.9
Zinc	0.82	1.5	1.4	1.4	2.5	0.44	1.3

*Note: Above data is with respect to solid-state pyrotechnic composition, not products of combustion.

Experimental work performed by Marlair consisted of measuring the combustion products of burning smoke powders with the aid of a calorimeter[37]. Unfortunately for this review, these powders are not representative of U.S. consumer fireworks. Consequently, specific experimental results are not relevant here; however, the method of measuring combustion products with the use of a calorimeter is precisely the type of experimental effort needed to begin quantifying toxicity for a product of interest. Although Marlair's experimental results on smoke powders are not presented here, a number of chemicals were identified as significant products characteristically emitted from burning fireworks (Table 5). Ultimately, more commodity specific data is necessary for U.S. consumer fireworks in order for a design engineer to estimate potential toxic exposure conditions for a fire occurring within a retail or storage facility.

TABLE 5. SIGNIFICANT PRODUCT EMITTED FROM BURNING FIREWORKS[37]

Type	Chemicals Emitted
Gases	CO_x, H_2, H_2S, CH_4, COS, N_2, NO_x, O_2, SO_2
Aerosols	Al_2O_3, $(NH_4)_2CO_3$, Sb_2O_3, $BaCO_3$, $BaSO_4$, Bi_2O_3, C, CuO, Fe_2O_3, MgO, KCl, K_2O, K_2CO_3, KNO_3, K_2SO_4, K_2S, K_2SO_3, KCNS, $SrCO_3$, $SrSO_4$, S, TiO

Research focusing on tenability with regard to thermal exposure from consumer fireworks is sparse. However, the critical limits of tenability are fairly well established. Overexposure to heat may result in heat stroke, skin burns or respiratory tract burns. For fires occurring in consumer fireworks retail and storage facilities, the duration of the exposure is expected to be short enough that heat stroke is not a primary area of focus for this report. Further, it is expected that skin burns will result prior to respiratory tract burns. Therefore, criteria for skin burns are used as the critical factor for assessing tenability in this application. According to Purser, a critical heat flux of 2.5 kW/m^2 is a critical threshold above which pain and burns will be sustained in a matter of seconds[34].

Sensitivity and Explosiveness

The terminology used to communicate the hazards posed by energetic materials as opposed to their reliable performance is in need of an increase in clarity. Recently, in the United Kingdom, the term sensitiveness was created to refer to the relative probability of an energetic material being ignited by a certain level of stimulus such as heat, friction or impact. In contrast, the term sensitivity is used to characterize the level of stimulus that reliably initiates a reaction. The similarity in syntax but contrasting context of these terms is further exploited by the fact that many other countries such as the United States, Canada, Japan and Croatia use both terms interchangeably[38].

Pyrotechnic mixtures may be sensitive in varying degrees to both thermal and mechanical ignition stimuli. Such stimuli are commonly found in the form of heat, friction and impact. The quantification of sensitivity to such stimuli is particularly important to the development of safety guidelines for material handling and storage. Estimating sensitivity with respect to mechanical stimuli such as impact and friction may be performed experimentally for specific products. Common methods for such testing include simple variations on a drop test in which the work absorbed from impact is estimated as a function of the height from which the product is dropped[31]. In such tests, it is important that any bouncing of the product on impact is accounted for when calculating the work absorbed. Sensitivity with respect to friction is most commonly tested with machines imparting rotary friction or electric sparks to the product.

Although sensitivity to mechanical stimuli is certainly significant with respect to addressing general ignition stimuli, thermal sensitivity is especially important within the scope of this review. This is due to the primary focus on hazards related to heat exposure occurring within the built environment. Although data addressing thermal sensitivity is available for individual devices, it is recognized that exposure to heat from fire in the built environment will likely occur with the material in a final packaged condition. Generally, such additional packaging will insulate the device from exposure to heat; however, the insulating quality of the packaging will depend heavily on factors such as the thermal thickness and thermal diffusivity of the material[39]. Modern thermal sensitivity studies typically focus on innovative ignition techniques exclusively using infrared radiation. This is problematic from the standpoint of fire protection because not only does such data typically focus on more highly energetic materials than those which are used in consumer fireworks; but also the effect of packaging acting as an insulator to the chemical composition is not explored. It is worth noting that the Japanese National Institute of Advanced Industrial Science and Technology (AIST) is currently developing a physical hazard database on the safety of fireworks materials, though this effort focuses primarily on characteristically higher energy explosives than those meeting the definition of consumer fireworks[40].

In addition to sensitivity, it is important to examine the severity of the actual material output, also termed the explosiveness. There is no direct correlation between the sensitivity and explosiveness of a specific composition[1]. Generally, consumer fireworks will possess varying degrees of sensitivity at consistently low levels of explosiveness relative to display or military pyrotechnics. The explosiveness may be determined experimentally for stable mixtures. Generally, the output will be greater for the same mixture at a lower bulk density. Also, recognizing that deflagrations and detonations take place in the gaseous phase, mixtures evolving little or no gas will exhibit little or no explosiveness[31].

Effects of External Fire on Fireworks Stored in Steel Transport Containers

One of the first efforts to examine an enclosure fire with respect to consumer fireworks storage was conducted by Wyle Laboratories in conjunction with the U.S. Department of Transportation and the American Pyrotechnic Association in 1983. This testing program consisted of a total of two tests. For each test, a single 20-foot long steel shipping container packed with 15,000 pounds of consumer fireworks was subjected to an external fire exposure in the form of burning kerosene soaked wood pallets. The only significant difference in setup between the two tests was the placement of the external fire. During the first test, the fire was placed directly underneath the steel container thereby maximizing the imposed radiant, convective and conductive heating components (assuming ample oxygen was provided to the fire). The second test was conducted with the fire placed adjacent to the steel container such that the flame was blown onto the steel by the prevailing wind[41]. Consequently, the strength of the heat source was greater during the first test due to the increased magnitude of radiant and convective heating components.

Fireworks inside the steel containers ignited during each test after several minutes. The duration of the fire within the steel container was approximately 1 hour in each case. This makes sense assuming that the type and proportions of fuel and oxidizer was nearly identical in each of the two tests. This trend is further confirmed by similar measurements of maximum gas temperatures within the space (1,400°F in test 1 and 1,598°F in test 2). Additional results included the measurement of a peak pressure of 3.66 psig in the first test, which was nearly double the 1.9 psig recorded in the second test. This may be the result of local differences in gas dynamics such as the location of the actual flame with respect to the instrumentation, or perhaps an effect of air infiltration caused by the prevailing winds. Regardless of the reason behind this measurement, the more significant point to be made is that neither test resulted in an explosion. The rate of total fuel consumption was also quite slow in each test; however, no measurements were taken regarding the deterioration of tenability within the space. Such measurements should be taken during future research efforts as transient tenability and available time for egress is a pertinent fire protection concern. Nevertheless, the lack of either a detonation or an explosion in these tests is an excellent illustration of the output that is typically expected from consumer fireworks.

Almost 20 years later, the Health and Safety Laboratory of the United Kingdom conducted a second similar series of tests[42]. This new program was conducted in response to catastrophic explosions in European facilities where highly energetic materials (not consumer fireworks) were stored and manufactured. However, the testing series devoted one of the three total tests to the evaluation of hazards related to consumer fireworks for the purpose of comparison. The experimental setup for these tests was quite similar to the 1983 experiments by Wyle Labs. Steel ISO transport containers packed full of various types of fireworks were subjected to an external heat source in the form of a wood and kerosene fire ignited adjacent to the container. The types of fireworks utilized are presented in Table 6 (Note that at the time of testing, shells were classified as 1.4G under the UN scheme. This was revised to 1.3G as a result of Myatt's research). It should also be noted that most of the materials in Test 2 and all of the materials in Test 3 were significantly more energetic than what would be considered consumer fireworks in the United States.

TABLE 6. FIREWORKS LOAD IN UK TEST

Test	Fireworks Description	No. Cases	Gross Weight (kg)	NEC (kg)	UN Class (At time of testing)
1	British consumer fireworks	72	1,000	228	1.4G

The results of the first test (which involved consumer fireworks exclusively) were in good agreement with general trends observed by Wyle Laboratories in 1983. Ignition of the fireworks within the container occurred after several minutes of heating from the exterior fire. No explosions occurred at any time during the incident and peak recorded pressures were only slightly above ambient. Of particular interest in this test was that sporadic ignitions of fireworks continued for a total of 17 hours after initiation of the test. When the doors of the container were opened at the 18-hour mark, researchers found the predominant pattern of charred packaging providing insulation for pyrotechnic contents inside. The fire soon flared up and the door to the container was closed as the test resumed with countless devices discharging inside. This occurrence suggests that the fire inside the steel container began as a packaging fueled fire that quickly ran out of oxygen inside the space. This phenomenon is significant from a fire protection perspective because it suggests that traditional means of suppression would be effective during this stage of development, so long as ventilation to the space was limited and the fire did not spread to the pyrotechnic fuels.

Explosions were observed in each of the remaining tests, due to the presence of significantly more energetic materials in the transport containers. At the time these tests were conducted, some of these more energetic devices fell under the 1.4G classification with respect to the UN recommendations. The results of these tests revealed that confinement of bulk storage might increase the output of explosive devices. This occurrence prompted changes to the UN recommendations that included more strict delineation between the 1.4 and 1.3 explosive classifications.

A robust research project on the Quantification and Control of the Hazards Associated with the transport and storage of Fireworks (CHAF) was recently sponsored by the European Union (EU). This coordinated effort, undertaken by the Health and Safety Laboratory (HSL) of the United Kingdom, the TNO Prins Maurits laboratory of the Netherlands and the German Federal Institute for Materials Research and Testing (BAM). In response to a number of severe loss incidents related to the storage of high energy explosives (not consumer fireworks), the major objectives of the effort included an investigation of the effects of packaging and storage configuration on output severity. Consumer fireworks were not a major focus of this effort due to the relatively sparse loss history worldwide. Nonetheless, some attention was given to these characteristically less energetic devices in the thorough exploration of the project objectives[43].

Among the studies potentially relevant to consumer fireworks storage was a single test, conducted as part of a larger program, exploring the results of an enclosure fire occurring within a steel and concrete depot loaded with UN Class 1.4G fireworks. The storage magazine utilized for the test was of modular construction with concrete filled steel casing panels with a floor surface area of 10 square meters. The roof was equipped with a dense grating (20 mm x 20 mm openings). The magazine was loaded to full capacity (except for a central access aisle) with UN Hazard Division 1.4G fireworks in an effort to mimic a fuel load typical of Polish consumer fireworks (Table 7). The total fuel loading corresponded to a Net Explosive Mass (NEM) over 1,000 kg. According to contemporary Polish regulations, such a scenario occurring in the real world would require minimum separation distances of 10 meters from magazines and production buildings (with or without explosives) and 15 meters from local roads, motorway and main roads and inhabited areas[44].

TABLE 7. POLISH CONSUMER FIREWORKS USED IN CHAF TEST

Type	Description
Batteries	≤ 300 g pyrotechnic composition, caliber ≤ 30 mm (1,2")
Roman candles	caliber ≤ 12 mm (0,5")
Rockets	≤ 20 g pyrotechnic composition
Fountains	≤ 100 g pyrotechnic composition
Bangers	≤ 5 g pyrotechnic composition
Low hazard fireworks and novelties	None given
Sets of fireworks	None given

Ignition of the fireworks was achieved with the use of a powder charge and electric primer. Test results were tabulated in the form of observations made from the exterior of the storage magazine. A timeline of these results is presented in Table 8.

TABLE 8. TIMELINE OF RESULTS FROM POLISH CONSUMER FIREWORKS TEST

Time period	Event
12 minutes - 2 hours	Start of individual explosions, from time to time series of small explosions, visible smoke around roof
2 - 3 hours	Distinct explosions of changeable intensity heard from a distance of 500 meters. No mass explosion. Roof stays in place. Visible smoke emission observed. Concrete temperature at outside surface of magazine measured at 50°C.
3 - 4 hours	Slow process of burning fireworks, cartons, plastics without distinct flames or explosions. Weak smoke emission increased only in the case of oxygen intake when door is opened.

These results indicate a period of approximately 12 minutes following ignition in which conditions within the space are unknown. The lack of observations at the exterior implies a slow growing fire within. Ultimately, the researchers noted no significant damage to the containment vessel following active suppression after 8 hours. It is important to note that the timeline of this event is significantly longer than would be expected for an enclosure fire involving simple packaging materials. The reason for this is that these materials require an oxidizer in the form of air to sustain combustion. This is not the case for the actual fireworks, which are equipped with their own oxidizer as part of the pyrotechnic composition. As a result, the combustion of the packaging is heavily influenced by the rate of ventilation into the magazine whereas the fireworks are not directly dependent on this parameter. In other words, if the door to the magazine is opened and the rate of reaction in the packaging increases, the fireworks will be exposed to additional heat from their surroundings and perhaps become involved in greater numbers. In this way, combustion of the packaged fireworks may be indirectly dependent upon the ventilation to the room. In any case, structural damage was nonexistent as a result of this test.

Enclosure Fire in Simulated Consumer Fireworks Retail Setting

The State of Washington created new regulations in 1995 for building planning with respect to consumer fireworks retail facilities. These new regulations included requirements for construction type and property line setbacks based upon purely qualitative assessments. In response to these new regulations, a testing program was undertaken to provide more quantifiable rationale. The program included a single test in which a full size temporary retail stand was filled with consumer fireworks. The 128 square foot structure (8 ft. x 16 ft.) was built of pre-assembled 4-foot sections of ¼-inch thick plywood over 2-inch x 2-inch framing. The stand was provided with dual 28-inch wide side doors that were shut during the experiment. The only other opening in the facility spanned the entire 16 ft. length of the front of the structure from counter height (4 ft.) to ceiling height (7 ft.). The total area of this opening was therefore 48 square feet. Inside the stand, over 10,000 individual pieces totaling approximately 900 pounds of consumer fireworks were stocked on plywood shelving (Table 9)[45].

TABLE 9. LOADING OF SIMULATED RETAIL FIREWORKS STAND

Description	Quantity	Shots
Variety Packs (10 separate devices)	2	20
Novelty items	909	909
Ground spinners	1,440	1,440
Fountains and whistles	951	951
Cones	64	64
Spinning wheels	6	6
Smoke devices	792	792
Metal stem sparklers	396	396
Year-round novelty items (including poppers)	440	440
Helicopters	3,528	3,528
Parachutes	290	290
Candles	864	8,362
Mortars/Shells	120	384
Large night displays (cakes)	303	7,106
Total	10,105	24,688

Rain occurred at the test site for 3 days prior to and even during the actual test. The stand was loaded on the morning of the test and therefore although the wood structure possessed high moisture content, the loading was exposed to these humid conditions for a much shorter time period. The test was initiated by the ignition of newspapers within the shed. A timeline of significant events following ignition is provided in Table 10.

TABLE 10. TIMELINE OF EVENTS FOR FIREWORKS STAND EXPERIMENT

Time [sec]	Event
0	Ignition
250	Packaging ignites, 400°C temperature at origin
550	Ignition of fireworks, temperatures inside stand rise to 800°C and fireworks exit open front of stand
567	Visibility within stand near zero. Ignition of fireworks more rapid. Number exiting stand keeps increasing. Heat flux from front of stand is 7 kW/m^2 at 14 feet
617	Flashover. Max temperature inside stand is 1,400°C. Heat flux rises and so does number of fireworks exiting stand
866	Temperature inside stand is 1,100°C. Structure actively burning, with collapse imminent. Very few fireworks still active. Heat flux of 22 kW/m^2 recorded at 14 feet from opening, temperature 200°C
2100	Temperature recorded at 550°C inside stand, test ends.

Measurements taken during the experiment included both interior and exterior temperatures as well as incident heat flux at various exterior positions around the stand. Additionally, from the measurements of incident heat flux, researchers estimated this quantity as a function of distance from the fire within the stand. This data has been digitized from the initial publication and is represented, with annotations, in Figures 3, 4 and 5.

FIGURE 3. TEMPERATURES DURING FIREWORKS STAND EXPERIMENT

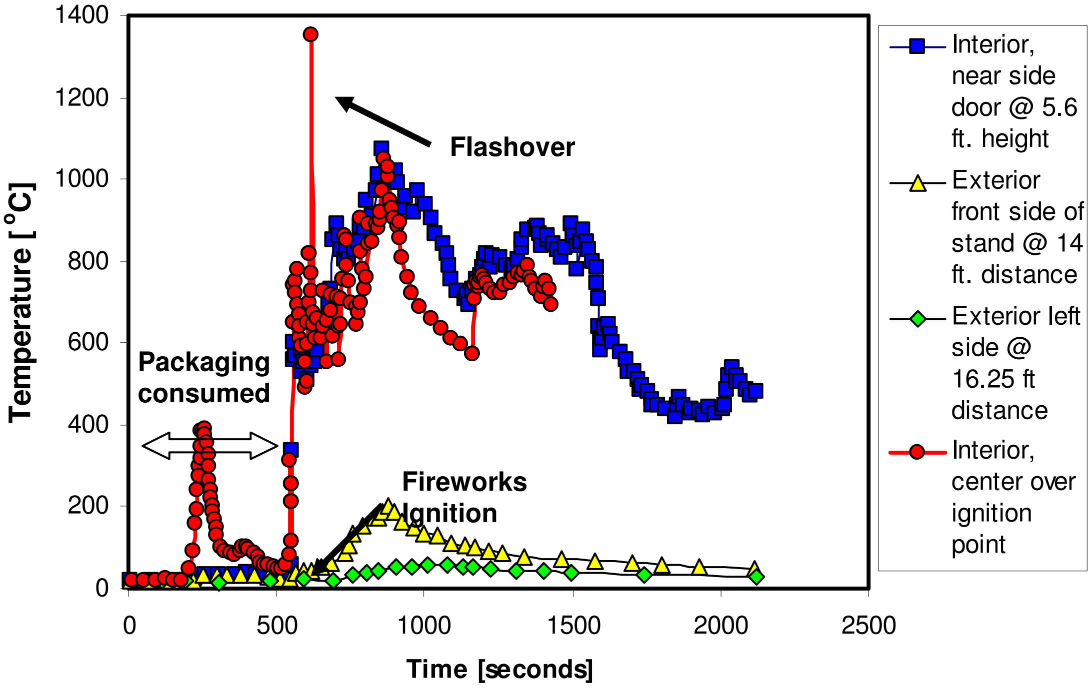


FIGURE 4. TRANSIENT HEAT FLUX DURING FIREWORKS STAND EXPERIMENT

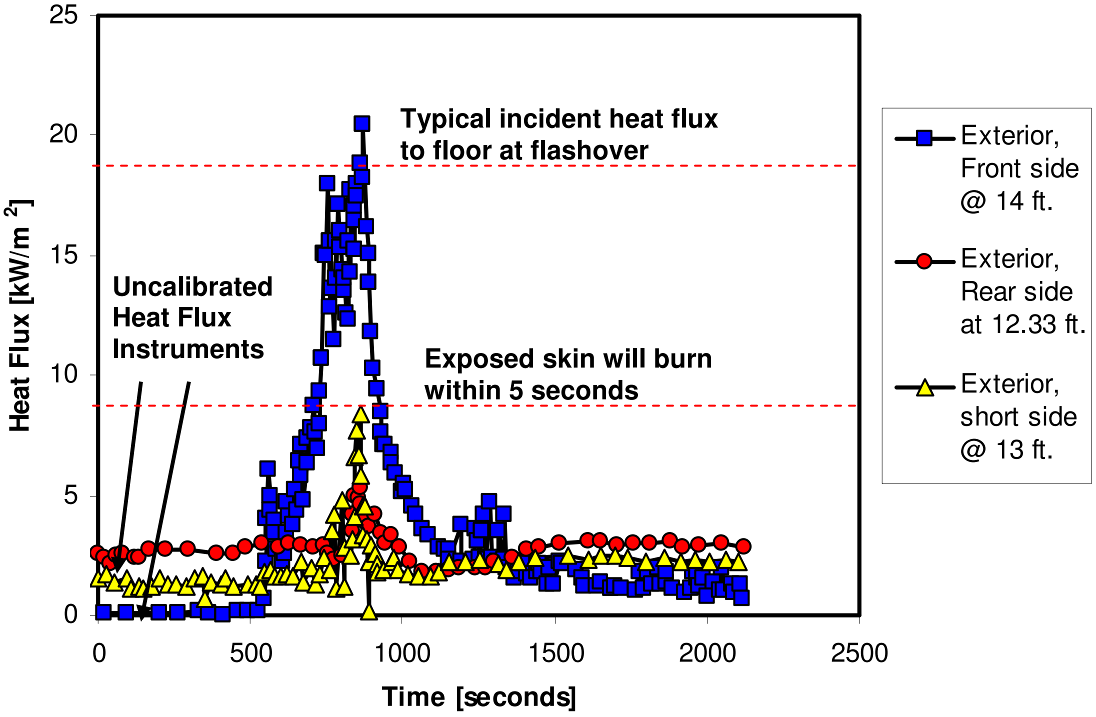
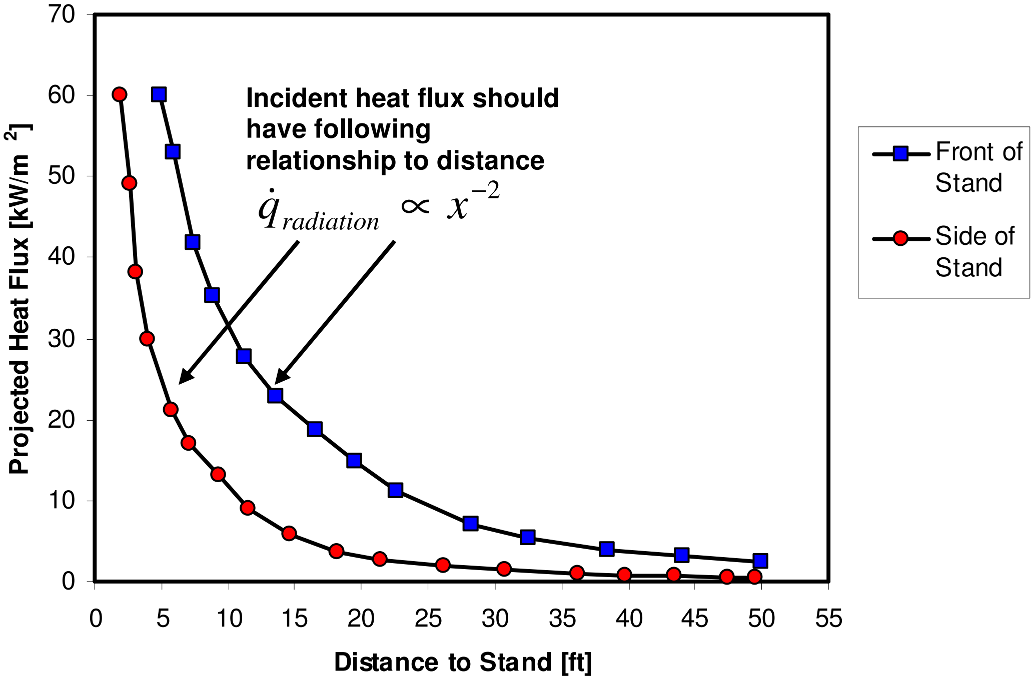


FIGURE 5. SPATIAL HEAT FLUX PROJECTED FROM EXPERIMENTAL DATA



Significant events such as the ignition of fireworks and the onset of flashover can be visualized from the temperature data in Figure 3. Similar to the previously discussed tests conducted in steel transport containers, the period of fireworks involvement is preceded by several minutes of early fire growth, likely involving ordinary packaging materials. During this stage of growth, the fire would probably be quite controllable by automatic sprinkler protection and normal egress would be expected. However, following this initial period, unlike the experiments conducted in the steel transport containers, flashover occurs in this retail stand within about 1 minute of the first pyrotechnic ignition. One explanation for this apparent discrepancy is the availability of ample airflow via the 48-ft^2 opening in the front of the stand. While the pyrotechnic mixtures contain their own oxidizers, during the early stages of fire development packaging is the primary fuel source. As a result, airflow into the space is critical to early fire growth. In the case of the tests involving steel ISO transport containers, the supply of oxygen within the container, which had no significant openings, was completely consumed rather quickly. The result was a packaging fire that did not fully transition to heavy involvement of the pyrotechnic contents until the doors of the container were opened 18 hours later.

When ignited in a method consistent with their design (i.e., by fuse), the combustion process for consumer fireworks is rapid. Such was the case in the Scottown, Ohio incident where the enclosure fire was started by the deliberate “ignition by design” of fireworks devices. Resulting fire growth within the store was quite rapid in a manner similar to the Washington simulation. However, had the ignition source been an ordinary hazard fire which gradually raised packaging and contents to their auto-ignition temperature, it is possible that this catastrophe may have been preceded by an early stage of growth during which traditional methods of fire protection may have been effective.

The presentation of data regarding incident heat flux leaves some important questions unanswered. Measurements taken at the exterior short side of the stand and the exterior rear side of the stand indicate an incident heat flux level of roughly twice what would be expected during the hottest part of a sunny day on a Florida beach (Figure 4). During the test, however, persistent rain was noted. Consequently, the calibration of these measurement devices must be called into question. Information regarding the instruments was not published in the report. On a separate but related note, the projections of spatial variations in incident heat flux should both follow basic heat transfer theory. It appears that the curves presented in Figure 5 follow slightly different patterns of decay, neither of which corresponds precisely to the theoretical relationship between radiant heat flux and distance.

Ultimately, the authors of the study concluded that these projections of incident heat flux as a function of distance from the stand supported implementation of 40-foot setback requirements. On the basis of incident heat flux alone, this seems reasonable; however, the authors failed to focus on the fact that several aerial devices were propelled through the front opening of the stand and landed over 250 feet away. This projectile hazard implies that either setback criteria should be re-evaluated or a method for mitigating this additional hazard should be investigated.

Packaging Effects

Packaging of multiple devices under the 1.4G classification includes a double-wall corrugated fiberboard box up to a weight of 35 kg per packaging. In the U.S., the method of construction of individual devices is specifically regulated by the DOT in conjunction with APA Standard 87-1 which stipulates further material requirements (i.e., cardboard of heavy paper cones for cone fountains, paper-wrapped or cardboard tubes for firecrackers, etc.). Packaging for consumer fireworks essentially encapsulates the commodity within paperboard, cardboard, plastic wrap or similar materials. The intent of this encapsulation is to protect the fuse of the device(s) and insulate them from accidental ignition while the item is on display. Ultimately, the pyrotechnic composition is insulated by the casing of the device (i.e., heavy walled tubes of a roman candle), additional display packaging and even the 4G fiberboard box in some applications (i.e., transport and storage).

An enclosure fire occurring within a storage or retail facility containing high energy explosives (not consumer fireworks) may result in an accelerating propagation of the reaction throughout the inventory. For this reason, the bulk storage of high-energy explosives poses significant risks above and beyond the safety hazards of an individual device. Packaging parameters such as construction of the device, ratio of pyrotechnic to inert material, type of pyrotechnic material and classification of the packaged product are all known to factor prominently in the extent and magnitude of propagation[46]. Specifically, classification of the packaged product plays a very important role for consumer fireworks, which by their very nature are limited in output. As a result, the mechanical, thermal and shock propagation mechanisms exhibited by high energy explosives may be reasonably assumed to be of far lesser magnitude or even altogether absent when consumer fireworks are under consideration. However, more research is recommended with respect to the energetic properties of small amounts of flash powder in order to make this assumption with complete confidence.

Ultimately, this assumption leads to the conclusion that the main mechanism for fire growth and spread in an enclosure fire involving consumer fireworks is the fire itself. This having been said, it is important to recognize that the packaged combustion of metals equipped with oxidizing agents will likely increase temperatures and heat fluxes beyond the maximum limits otherwise in play for a ventilation limited fire. Note that a similar concept prevails for fire protection of oxidizers in storage.

Effectiveness of Automatic Sprinkler Systems

In 1997, following the disastrous events of the Scottown, Ohio incident, the Ohio General Assembly legislated the formation of the Fireworks Suppression Systems Task Force. The objective of this group was to identify and analyze the efficiency of common fire suppression systems with respect to fireworks sales display areas. The study was limited to water-based fire suppression systems for the sake of practicality. Ultimately, a total of 2 full-scale tests were performed by Battelle (referred to as Battelle tests throughout the remainder of this report)[47].

The task force devised very specific definitions of the term effectiveness in an effort to provide a basis for evaluation of performance. Effectiveness was defined to pertain to either fire suppression or fire control, which is an established concept in NFPA 13 *Standard for the Installation of Sprinkler Systems*. In this standard, fire suppression is defined as “sharply reducing the heat release rate of a fire and preventing its regrowth by means of direct and sufficient application of water through the fire plume to the burning fuel surface” (1996 was contemporary version of the standard although definition in the current 2007 edition remains the same). Criteria for fire control were delineated on the basis of tenability within the fire enclosure. The criteria for tenability were identified as a maximum gas temperature of 200˚F and maintenance of a smoke layer height of 6 feet above all walking surfaces for a period of 20 minutes.[48]

It should be stated that such criteria are not provided in NFPA 13 and that maintaining tenability within the room of fire origin in this manner is an uncommonly conservative fire protection engineering design objective. This is especially true of the criterion for maintaining the smoke layer interface at a height of 6 feet for 20 minutes. This criterion is specific to smoke control system design criteria. What is particularly interesting to note about the reference to this criteria is that it is also used in the 2006 International Building Code (currently by far the most widely used building code in the United States); however it is used in reference to maintaining tenable conditions in the upper atmosphere of atria where high level walking surfaces serving as paths of egress may communicate with the smoke layer. The geometry of consumer fireworks showrooms (particularly as shown in Figures 2A, 2B and 2C in this report) is far different. Application of a smoke layer height objective in these small volume spaces is impractical even for more typical mercantile, business or storage fuel loads. In other words, if the fireworks were removed entirely from the fuel package and the only commodity remaining was the packaging, this criterion would still be a mismatch.

The test sequence was aimed at exploring the effects of suppression systems on the accidental ignition of a load of 1.4G fireworks similar to what would be found in a 1,000-ft2 showroom. The exact dimensions were 22.25 ft x 45 ft with an 11 ft 8 in ceiling. On the short side of the enclosure, a single 36 in x 80 in door was left open to provide make-up air for a smoke control system, which was designed to provide exhaust per the previously cited tenability criterion. The room itself was built of ½ inch thick gypsum wallboard mounted on an outer frame of 5” x 5” steel tubing. The ceiling of the enclosure was a standard drop ceiling of UL listed commercial grade acoustic material with a flame spread rating of 25.

Fireworks were stored on gondola shelving with base shelves 26 inches deep and top shelves 16 inches deep. The units had 4-foot long sections assembled in groups of 3 for each aisle. Overall, a total of 3 gondola units were used; 2 of which were positioned along the enclosure walls with a central unit positioned across an open 6-foot wide aisle on each side[49].

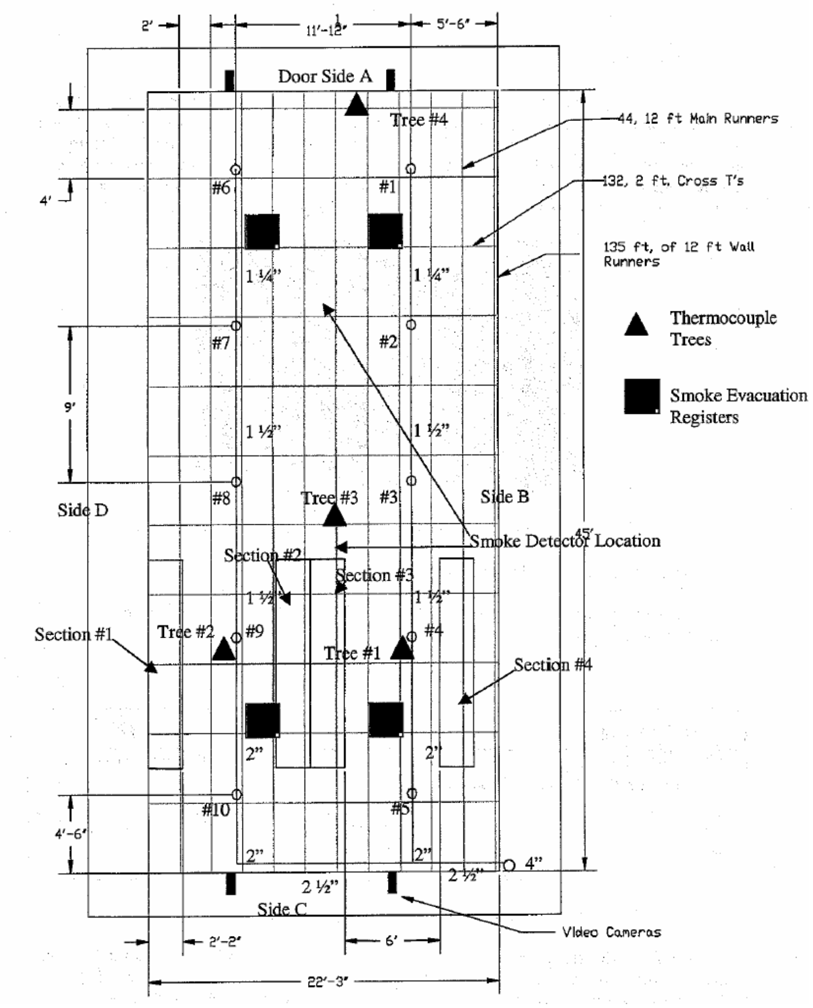
Active fire protection features within the enclosure included a smoke exhaust system that was designed to operate at a flow rate of 7,700 cubic feet per minute. This flow was distributed across a total of 4 square exhaust inlets of 2 ft length. The exhaust was activated by smoke detection within the space. In addition to the smoke exhaust system, automatic suppression was provided with pendant sprinklers protruding through the drop ceiling tiles of the enclosure. Specifics of the showroom layout are provided in Figure 6.

Data acquisition during the test series consisted primarily of observations documented by still pictures and video, measurements of transient gas temperatures (4 separate vertical profiles as shown in Figure 6) and transient heat flux (1 test only). The standard fireworks array was arranged as shown in Figure 6.

Although a series of preliminary tests were conducted with reduced fuel loading, the report does not include theory and validation of dimensional analysis to compare results at multiple system scales. As a result, these initial tests were useful for benchmark analysis only.

A total of 2 full-scale tests were conducted with the objective of evaluating the dependency of fire severity on the type of automatic sprinkler system provided. Unfortunately, the effect of the system was not properly isolated due to the fact that multiple system variables such as the fuel loading were changed between tests. Nonetheless, these results do provide important and rare insight into the effectiveness of common suppression systems for this particular application.

FIGURE 6. BATTELLE SHOWROOM LAYOUT



The first full scale test incorporated 150 cases of fireworks stored on the gondola type shelving with an NFPA 13 extra-hazard wet pipe sprinkler system installed overhead. The maximum area of coverage was 100 ft^2 with a slightly over-designed piping grid. Pendant sprinklers were utilized on drop downs throughout the room as illustrated in Figure 6. These sprinklers had a temperature rating of 155°F. It is significant that the test lab apparently received these fireworks unpacked and actually performed sorting and re-packaging of the fuel load. Details of this process were not provided in the report with the exception that this was done under the supervision of the task force.

Ignition was achieved with the use of a 4-ounce mortar increment situated atop an aerial repeater at the base of the 3rd row (central aisle) of shelving. Flames traveled up the height of the shelving unit in less than 3 seconds with smoke detection occurring 5 seconds after ignition. A complete list of observations is included in Table 11. The most significant observation to be made from this timeline is that untenable conditions are reached in less than 30 seconds following ignition and essentially prior to the activation of the sprinkler system, despite the intervention of smoke exhaust at the point of detection.

TABLE 11. BATTELLE FULL SCALE WET PIPE TEST TIMELINE

Time after Ignition [sec]	Event
0.00	Ignition
2.15	Flames engulf shelf above ignition point (2nd shelf)
2.65	Flames traveled to 3rd shelf
5.00	Smoke detection, activation of smoke exhaust
6.15	Fireworks jump aisle between Sections 3 and 4
8.32	Commodity dispersed into aisle between Sections 3 and 4, burns on floor
15.23	Flame spread interior to shelving between Sections 3 and 2
19.13	Smoke layer reaches 6 feet above walking surface
19.20	Fire jumps aisle between Sections 2 and 1
23.00	Drops of water on camera lens, but visibility to low to precisely pinpoint sprinkler activation
27.00	Room completely obscured by smoke

Damage to the test room included destruction of drywall and drop-ceiling tiles was evident from exposure to heat and the impact from projectiles throughout the space. Additional items deformed due to heat exposure included the gondola shelving holding the commodity, smoke detectors and the steel studs on which the drywall was mounted. Ultimately, a secondary sprinkler system was utilized to control the fire in the laboratory. Transient temperature data taken over the span of approximately 2 minutes following ignition reveals maximum gas temperatures on the order of 1200°F interior to the room with a maximum of 600°F at the doorway. Given that all of this occurs essentially prior to sprinkler activation, this particular test provides a baseline result for analysis. Comparing these results to a fire within a similar enclosure in which only the packaging is involved could be done to comprehensively evaluate the influence of the actual commodity on the hazard severity. Even without such a specific comparison readily available, at first observation, it seems quite reasonable to assume that the speed of hazard development in this test is significantly beyond what would be expected for a fire involving only the commodity packaging.

The second full scale test undertaken involved the burning of 170 cases of fireworks arranged in a similar manner as the preceding test; however, the exact fuel loading in terms of the quantities of specific device types was not implemented. The report contends that the total fuel load within the space was equivalent to the first full-scale test. This second test utilized Early Suppression Fast Response (ESFR) sprinkler system protection again with a maximum coverage area of 100 ft^2 per sprinkler. Specific sprinklers used had a temperature rating of 165°F and a K factor of 25.

This second test began with a new ignition method involving a redundant means for ignition. The method included 3 electric matches attached to a 110 shot aerial repeater with a crank initiator box. This new method of ignition again resulted in rapid flame spread and growth; however, detailed observations of this early growth were not provided in the report. The first automatic sprinkler (Sprinkler #4) intervened 15 seconds after ignition followed by a second and third at 22 and 31 seconds, respectively. At 35 seconds after ignition, all sprinklers within the room of origin had activated. Ultimately fire did spread across both aisles although some of the commodity in Sections 1, 2 and 3 remained unburned at the conclusion of the test. The smoke exhaust provided during this test was apparently overwhelmed as significant leakage to the larger laboratory occurred. Both thermal and projectile damage to the walls of the fire enclosure and ceiling mounted smoke detectors were noted as minimal. The secondary sprinkler system was not utilized during this test.

Ultimately, the full-scale test with ESFR sprinkler protection yielded control of fire spread, although tenability objectives were not attained. Gas temperatures at a height of 10 feet above the walking surface were held below 200°F throughout the enclosure for essentially the entire duration of the test. This suggests that the space was thermally tenable during this time period. The recommendations contained in the test report noted that the smoke layer within the space dropped below 6 feet above the walking surface. This result was the product of multiple circumstances. The first, which was cited in the report, was evidence of exhaust inlets clogged with solid debris. In addition, the rate of smoke exhaust was calculated based upon an arbitrary design rate of heat release for the fire (2,000 Btu/second). As a result, the system would be overwhelmed if the actual rate exceeded the assumed rate of smoke production. Finally, several automatic sprinklers activated during this event. The spray from these sprinklers entrains a considerable amount of surrounding gas including both air and smoke. The result is a negative effect from the sprinklers on the maintenance of a clearly defined layer height despite their suppressing function. Maintenance of a well-defined layer interface under such conditions is unrealistic.

Fire Protection Engineering Design for Large Distribution Centers

Large distribution centers (such as the K Mart distribution center involved in the aerosol fire in Falls Township) characteristically include high-density fuel loading over a large floor area with a relatively low occupant load. This is a unique application in fire protection engineering because it represents a rare case in which the primary focus is related to property protection. This is not to say that protection of life does not take precedence, but rather that protecting a low occupant load of essentially trained personnel is not anticipated to be as challenging an objective as the task of preserving large amounts of product. However, in the case of consumer fireworks, the protection of property in structurally and thermally isolated retail sales and storage facilities is an objective that is often discarded altogether. In other words, life safety is the exclusive objective of fire protection in these applications.

A recent study performed by the Canadian Explosives Research Laboratory (CERL) explored the proposed operations for the conversion of an existing warehouse into a facility used for consumer fireworks wholesale distribution from a fire protection perspective[50]. The proposed 6,000-m^2 warehouse was both structurally and thermally isolated from any neighboring facilities. A total fuel load of 1 million kilograms of Canadian consumer fireworks was to be stored within the facility with a total occupant load of between 10 and 15 employees.

The fundamental construction type of the warehouse was noncombustible with an unprotected steel frame on a concrete slab. On the interior, the warehouse was divided into lateral zones by cement block and sheet metal partitions, respectively. Several exits were distributed along the exterior walls of the facility. Features of fire protection included portable fire extinguishers, 5 cm diameter fire hoses, and automatic fire sprinklers located both at ceiling level and in-rack installations[50].

The method of storage included steel racks 4.9 meters tall, 1.2 meters deep and 3.7 meters wide. It was proposed that each rack would contain one shelf at a height of 1.5 meters and another at a height of 3 meters above the floor. The general method of storage proposed was to have each shelf (as well as storage directly below on the floor) support three pallets with each pallet containing solid piled cases of fireworks to a height of 1.4 meters. However, no commodity was stored above a height of 1.8 meters in the picking area. Commodity in both the picking and packaging areas was limited to 600 kg Net Explosive Quantity (NEQ). In-rack sprinkler protection was provided in all 3 zones of the warehouse where rack storage was implemented. The installation proposed was on the second shelf of each unit with overlapping spray areas with twice the number of sprinklers provided in the picking area as opposed to the storage area. No storage was proposed for the packing area. A minimum aisle width of 2 meters was typical throughout the storage and picking areas[50].

The warehouse also was equipped with loading docks fronting a receiving/shipping area in which a quantity limit of 600 kg NEQ was proposed. This area was planned for unloading of 12.2 m x 2.42 m x 2.42 m steel ISO transport containers packed fully with a potential load of up to 13,700 kg of packaged consumer fireworks. Proposed operations for the facility included receipt of consumer fireworks at the loading docks, unloading of the fireworks, distribution into the storage area, removal from the storage area to the picking area, removal from the storage area to the packaging area and shipping out[50].

Based on the list of operations and the provision of previously cited fire protection features inside the warehouse, a single worst-case design fire scenario was identified. This scenario corresponded to ignition of the contents of a fully loaded and sealed transport container. Separate research efforts conducted by Wyle Laboratories in the State of Washington as well as by the HSE, as previously discussed in this report, were cited as reference material for anticipated fire behavior[41,42]. Essentially, the lack of explosive behavior as exhibited in these experiments was cited in conjunction with the segregation of commodity, low loading densities, presence of fire suppression systems and established safety procedures were cited as sufficient justification for the distribution center[50].

It is certainly possible that the proposed design of the warehouse and accompanying operations were reasonable; however, only limited justification was given. This is perhaps most evident in the absence of design analysis or calculations for fire growth and spread and the corresponding design of automatic sprinklers both at the ceiling and at in-rack installation points. Experimental data regarding commodity specific fire behavior in rack storage (i.e., effects of storage height, rack geometry and relative sprinkler geometry on the burning rate) was and is still absent from available literature sources. Consequently, in the absence of experimental data or scientific theory, the adequacy of automatic fire sprinkler protection for this facility was not quantified. As a result, the worst-case fire scenario may well have been misidentified.

It is clearly important for this study to establish that the commodity did not exhibit explosive behavior; however, the necessary design objectives are farther reaching. In the absence of explosive behavior, the generation of heat and products of combustion for a fire occurring within the warehouse would seemingly pose the most credible threat to life safety inside the facility. While, it is certainly possible that the features provided were sufficient to mitigate plausible scenarios, the absence of analysis in this area is problematic. The research ultimately does not provide designers of fire protection systems for similar applications with tangible design criteria or rationale. For instance, a time-based egress calculation compared to an analysis of the deterioration of tenability within the space could have been used to quantify the adequacy of protection. Unfortunately, given the general absence of experimental data for consumer fireworks burning in rack storage configurations, such calculations would still have been simple estimates without validation.

HAZARD DATA

As evidenced by a number of very large loss incidents involving commodities such as aerosols, solid and liquid oxidizers and flammable and combustible liquids, segregation of materials according to the relative severity of fire-related hazards is an essential design practice. However, such segregation requires differentiation on the basis of specific knowledge of the hazards presented by each material. Such knowledge may be gained by either experimentation or theoretical derivation. Since it is simply not practical to conduct experiments focusing on every material in a given storage inventory, this knowledge is most often gained from reference material. Such material is often written with very specific classification objectives, which must be appreciated in order to properly apply the information gained. The following is a discussion of available hazard data for consumer fireworks as used for fire protection engineering purposes.

Flash Powder

To date, there exists no universally used definition of flash powder. The 2006 edition of NFPA 1124 (Section 3.3.32) references salute powder, which it defines as "an explosive composition that makes a loud report when ignited and constitutes the sole pyrotechnic mixture in a salute." Unfortunately, this definition yields little insight into the components of this energetic mixture. For the purpose of this review, it is useful to present the following more complete definition proposed by Conkling[54]:

FLASH POWDER – Pyrotechnic composition consisting of one or more oxidizers such as potassium perchlorate, potassium chlorate, ammonium perchlorate, barium nitrate, or potassium nitrate combined with 25% or more by weight of metal powder such as aluminum, magnesium, or magnesium/aluminum alloy ("magnalium"), or 30% or more by weight of a combination of metal powder combined with sulfur or antimony sulfide. The term "metal powder" means material capable of passing through a standard 275-mesh sieve.

The preceding definition of flash powder describes an explosive composition, the output of which is logically dependent on the amount of material. However in addition to output, one must also consider the sensitivity of the composition when assessing its hazardous properties. The sensitivity of flash powder compositions is generally expressed in terms of the ignition temperature of the composition, which can be manipulated by the use of different fuel and oxidizer combinations.

For these reasons, strict limits are placed not only on the maximum quantity of flash powder but also the allowable components of the mixture for use in consumer fireworks in many countries, with the perhaps the strictest limits existing in the United States. Around the world, potassium perchlorate and potassium chlorate are the most common oxidizers utilized in pyrotechnic compositions; however, note that among the chemicals specifically prohibited in the U.S. for use in consumer fireworks are chlorates except for use in firecrackers, toy caps, party poppers and in small items such as ground spinners wherein the total powder content does not exceed 4 grams of which not greater than 15% (600 mg) is potassium, sodium or barium chlorate (APA Standard 87-1). The standard composition in the U.S. possesses a sensitivity that is low relative to many other flash compositions. It typically contains potassium perchlorate, sulfur or antimony sulfide and aluminum. These limits are intended to reduce the hazard posed by individual devices containing flash powder; however, when these devices are displayed and/or stored in larger quantities, the role of packaging of each individual device as well as the bulk inventory certainly becomes quite important in slowing an otherwise very rapid reaction.

More research is needed in this area as well as in the exploration of how output and sensitivity depend on the physical, chemical and mechanical parameters of the composition. Density, granulation, purity, packaging and confinement have all been identified as primary variables of interest toward this objective[51].

U.N. Scheme for the Transport of Dangerous Goods[52]

Although the Fire Protection Guide to Hazardous Materials does contain important conceptual advances in the general classification of hazardous materials, little of its information is directly relevant to differentiation between pre-manufactured pyrotechnic devices and components. The method of this type of differentiation varies between sovereign nations with the most universally utilized method found in recommended model regulations published by the United Nations. These regulations for dangerous goods (synonymous with the term hazardous materials) are classified into numerically labeled categories based upon comprehensive chemical and physical characteristics. The UN regulations are intended to serve as the basis for segregation of materials as well as a limitation for material quantity during transport. It is important to note that the numbering scheme is independent of the severity of the hazard. Fireworks fall within material Class I, which is subdivided to further differentiate on the basis of output severity parameters including explosiveness and projection hazards (Table 12). All explosives are additionally assigned to compatibility groups. Generally, consumer fireworks fall within compatibility group G, which includes *"a pyrotechnic substance, or article containing a pyrotechnic substance, or an article containing both an explosive substance and an illuminating, incendiary, tear or smoke producing substance."* [52]

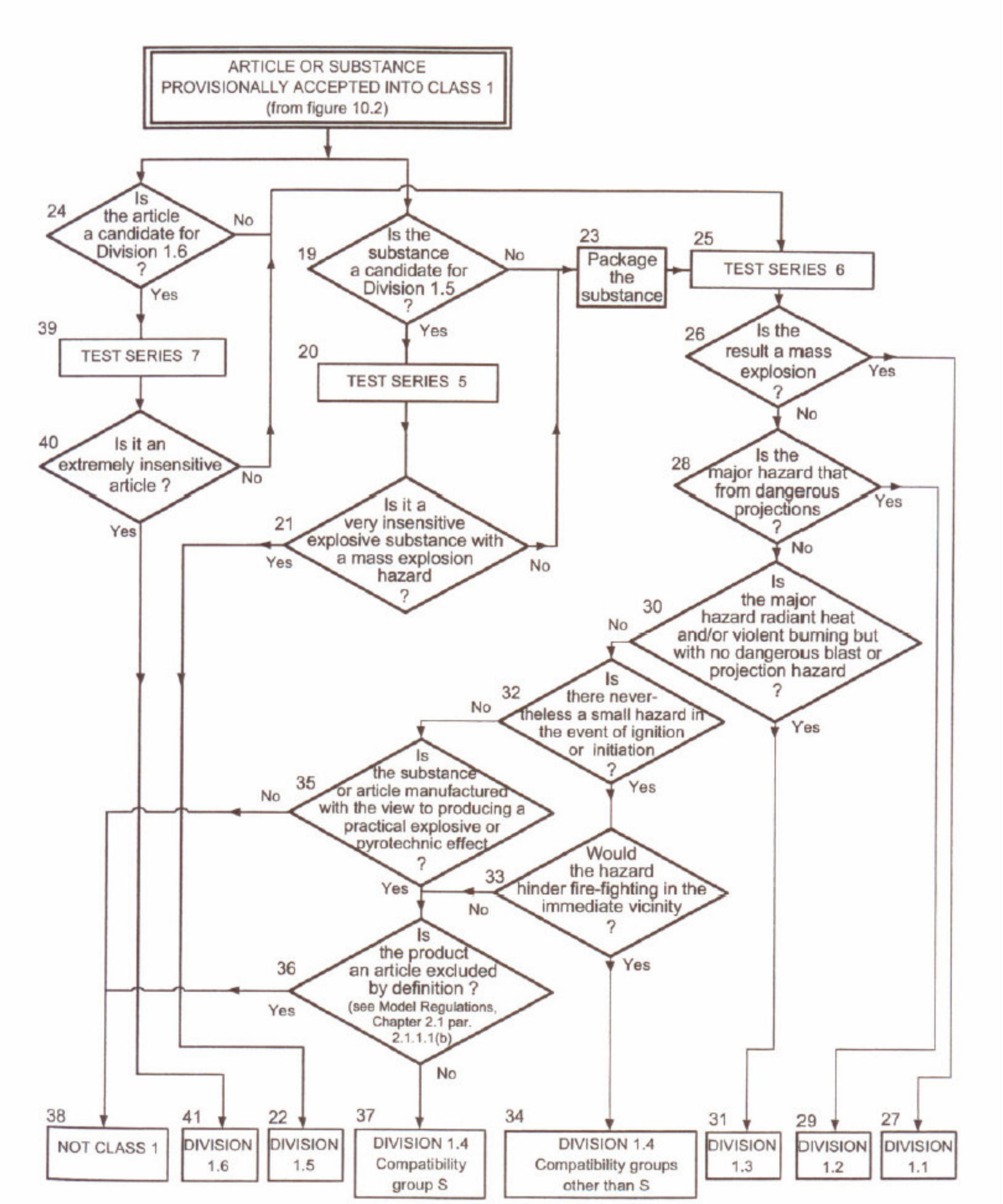
TABLE 12. UN CLASSIFICATION OF DANGEROUS GOODS (EXPLOSIVES)

Class	Description
1.1	Explosives with a mass explosion hazard
1.2	Explosives with a severe projection hazard
1.3	Explosives with a fire, blast or projection hazard but not a mass explosion hazard
1.4	Minor fire or projection hazard
1.5	An insensitive substance with a mass explosion hazard
1.6	Extremely insensitive articles

Based upon this classification scheme, most consumer fireworks fall under the category of 1.4G, while the 1.3G subdivision is reserved for the more powerful devices used in public fireworks displays. The basis of these classifications is derived from the results of standardized testing in accordance with UN criteria. According to the UN classification scheme (Figure 7), Division 1.4 explosives possess the following distinguishing hazard characteristics:

1. No mass explosion hazard
2. Major hazard is not from dangerous projections
3. Major hazard is not radiant heat and/or violent burning
4. There is a small hazard in the event of ignition initiation, which would hinder firefighting in the immediate vicinity.

FIGURE 7. UN PROCEDURE FOR ASSIGNMENT TO A DIVISION OF CLASS I[53]



In recognition of the wide range of fireworks in comparison to the availability of testing facilities and personnel, the UN recommendations further provide a default classification procedure. This procedure allows for classification on the basis of drawing an analogy to the established hazard characteristics of known articles. This analogy must be agreed upon by the competent authority. Limitations associated with the recommended default classification scheme include the stipulation that the method applies only to articles packed in fiberboard boxes. Mixed fireworks contained within the same package are to be classified according to the most conservative hazard division in the absence of specific test data. An excerpt from the default classification table is provided in Table 13, which lists only 1.4G classifications.

TABLE 13. UN DEFAULT CLASSIFICATION TABLE (1.4G CLASSIFICATIONS)

Type	Includes: / Synonym	Definition	Specification
Shell, spherical or cylindrical	Spherical display shell; aerial shell; colour shell; dye shell; multi-break shell; multi-effect shell; nautical shell; parachute shell; smoke shell; star shell; report shell; maroon; salute; sound shell; thunderclap; aerial shell kit	Device with or without propellant charge, with delay fuse and bursting charge, pyrotechnic unit(s) or loose pyrotechnic composition and designed to be projected from a mortar	Colour shell: ≤ 50 mm, or ≤ 60 g pyrotechnic composition, with ≤ 2% flash composition as loose powder and/or report effects
Roman candle	Exhibition candle; candle; bombettes	Tube containing a series of pyrotechnic units consisting of alternate pyrotechnic composition, propellant charge, and transmitting fuse	≤ 30 mm inner diameter, each pyrotechnic unit ≤ 25 g and ≤ 5% flash composition
Shot tube	Single shot Roman candle, small preloaded mortar	Tube containing a pyrotechnic unit consisting of pyrotechnic composition, propellant charge with or without transmitting fuse	≤ 30 mm inner diameter, each pyrotechnic unit ≤ 25 g and ≤ 5% flash composition
Rocket	Avalanche rocket, signal rocket, whistling rocket, bottle rocket, sky rocket, missile type rocket, table rocket	Tube containing pyrotechnic composition and/or pyrotechnic units, equipped with stick(s) or other means for stabilization of flight, and designed to be propelled into the air	≤ 20 g pyrotechnic composition, black powder bursting charge and ≤ 0.13 g flash composition per report and ≤ 1 g in total
Mine	Pot-a-feu; ground mine; bag mine; cylinder mine	Tube containing propellant charge and pyrotechnic units and designed to be placed on the ground or to be fixed in the ground. The principal effect is ejection of all the pyrotechnic units in a single burst producing a widely dispersed visual and/or aural effect in the air or; Cloth or paper bag or cloth or paper cylinder containing propellant charge and pyrotechnic units, designed to be placed in a mortar and to function as a mine	≤ 150 g pyrotechnic composition, containing ≤ 5% flash composition as loose powder and/or report effects. Each pyrotechnic unit ≤ 25 g, each report effect ≤ 2 g; each whistle, if any, ≤ 3 g
Fountain	Volcanos; gerbs; showers; lances; Bengal fire; flitter sparkle; cylindrical fountains; cone fountains; illuminating torch	Non-metallic case containing pressed or consolidated pyrotechnic composition producing sparks and flame	< 1 kg pyrotechnic composition
Sparkler	Handheld sparklers; non-handheld sparklers; wire sparklers	Rigid wire partially coated (along one end) with slow burning pyrotechnic composition with or without an ignition tip	Perchlorate based sparklers; ≤ 5 g per item and ≤ 10 items per pack; Nitrate based sparklers; ≤ 30 g per item
Bengal stick	Dipped stick	Non-metallic stick partially coated (along one end) with slow-burning pyrotechnic composition and designed to be held in the hand	Perchlorate based items; ≤ 5 g per item and ≤ 10 items per pack; nitrate based items; ≤ 30 g per item
Low hazard fireworks and novelties	Table bombs; throwdowns; crackling granules; smokes; fog; snakes; glow worm; serpents; snaps; party poppers	Device designed to produce very limited visible and/or audible effect which contains small amounts of pyrotechnic and/or explosive composition	Throwdowns and snaps may contain up to 1.6 mg of silver fulminate; snaps and party poppers may contain up to 16 mg of potassium chlorate/red phosphorous mixture; other articles may contain up to 5 g of pyrotechnic composition, but no flash composition
Spinner	Aerial spinner; helicopter; chaser; ground spinner	Non-metallic tube or tubes containing gas-or spark-producing pyrotechnic composition, with or without noise producing composition, with or without aerofoils attached	Pyrotechnic composition per item ≤ 20 g, containing ≤ 3% flash composition as report effects, or whistle composition ≤ 5 g
Wheels	Catherine wheels; Saxon	Assembly including drivers containing pyrotechnic composition and provided with a means fo attaching it to support so that it can rotate	< 1 kg total pyrotechnic composition, no report effect, each whistle (if any) ≤ 5 g and ≤ 10 g whistle composition per wheel
Aerial wheel	Flying Saxon; UFO's; rising crown	Tubes containing propellant charges and sparks-flame-and/or noise producing pyrotechnic compositions, the tubes being fixed to a supporting ring	≤ 200 g total pyrotechnic composition and ≤ 60 g pyrotechnic composition per driver, ≤ 3% flash composition as report effects, each whistle (if any) ≤ 5 g and ≤ 10 g whislte composition per wheel
Firecracker	Celebration cracker; celebration roll; string cracker	Assembly of tubes (paper or cardboard) linked by a pyrotechnic fuse, each tube intended to produce an aural effect	Each tube ≤ 140 mg of flash composition or ≤ 1 g balck powder
Banger	Salute; flash banger; lady cracker	Non-metallic tube containing report composition intended to produce an aural effect	≤ 1 g flash composition per item and ≤ 10 g per inner packaging or ≤ 10 g black powder per item

Although the UN system is intended to apply solely to the transportation of dangerous goods, many countries utilize this classification for further regulation of storage and licensing.

Classification of Fireworks in the United States

For approximately 2 decades prior to the publication of the UN default classification system, the United States has had its own such system in place. The system concept is similar in that it acts as a mechanism for efficient and conservative classification of materials in instances where specific testing is unnecessary. The system is based upon APA Standard 87-1, which is referenced (and therefore made the official classification document) by the United States Department of Transportation (DOT) regulations. A summary of this default classification system specifically with regard to 1.4G classification is provided by Conkling[54] as follows:

1. Fireworks may not contain any of the prohibited chemicals as listed in the definition of consumer fireworks provided in the definitions section of this report.

2. Limits are set for the total weight of pyrotechnic composition. Such limits apply to each individual tube/unit and are specific to item type (i.e., wheel, fountain, etc.). These limits are as follows:
   a. Firecracker – 0.050 grams
   b. Aerial report – 0.130 grams per report
   c. Roman candle – 20 grams
   d. Sky rocket – 20 grams
   e. Cone fountain – 50 grams
   f. Cylindrical fountain – 75 grams
   g. Wheel – 60 grams per driver / 200 grams total
   h. Mine – 60 grams
   i. Aerial shell or comet – 60 grams

3. The critical mass of pyrotechnic composition for cakes is set at 200 grams total. Cakes containing more than this amount are classified into Division 1.3 by default unless the device contains multiple tubes separated by a minimum 12.5 mm distance and a mass of up to 500 grams total is used.

4. Novelty items adhering to composition restrictions in APA Standard 87-1 are specially classed as novelties for domestic transportation. These items are exempt from Class I.

5. In addition to default limits for the total weight of pyrotechnic composition, specific limits are placed on the amount of flash powder permitted, including breaking or burst charges in aerial items. These limits are 50 mg per report for ground-based devices and 130 mg per report for aerial devices. If these critical values are exceeded, classification increases in severity to either Division 1.3 or 1.1 depending on the mass of flash powder.

An important issue raised by Conkling with respect to the American system is the potential for fiery projections exceeding 15 meters for certain devices (i.e., rockets, roman candles and aerial shells) subjected to the UN bonfire test, as this response is included as part of the design function of the device. Consequently, stricter limits are placed upon the mass of composition in the US system and the 15-meter limit for projectile distance is waived.

Recognizing that a significant percentage of fireworks imports into the United States originate in China, certain quality control measures have been instated by the combined efforts of the American fireworks industry and the federal government. One of the most prominent mechanisms is the American Fireworks Standards Laboratory (AFSL), which provides quality control testing services prior to the exportation of fireworks from China to the United States[54].

Authorization and Classification of Fireworks in Canada

The Canadian Explosives Regulatory Division (ERD) is the government entity responsible for authorization and transport classification of both consumer and display fireworks in Canada. In order to accomplish this objective, the Consumer and Display Fireworks Criteria standard is used in conjunction with the Explosives Act. The latter of these documents serves as the regulatory mechanism for authorization of explosives by the Chief Inspector, which is required for all manufacturing, storage, possession and transport within the country. Such authorization involves testing coordinated between the ERD and the Canadian Explosives Research Laboratory (CERL) when necessary[55].

In accordance with the Consumer and Display Fireworks Criteria standard, the following device types are acceptable for authorization as consumer fireworks (Class 7, Division 2, Subdivision 1) with detailed requirements on parameters such as packaging, labeling, structure, output, size, stability, composition and projectile debris for each device type:

- Battery/Combination
- Cakes
- Christmas crackers
- Flares
- Fountains
- Mines
- Pre-loaded mortars
- Roman candles
- Snakes
- Sparklers
- Ground spinners
- Strobe pots
- Hand-held fountains
- Toy piston caps
- Wheels

- Ground whistles

Secondary effects such as whistles and reports may be considered for authorization provided that they function exterior to the device.

Classification of fireworks for transport is based on both the UN Default fireworks classification table and the requirements of the Consumer and Display Fireworks Criteria standard; however, only slight differences between these documents exist for with respect to the 1.4G classification. These differences are summarized by Arpin[55] (Table 14). More significant differences between the classification methods are observed for display fireworks, which are not addressed herein.

TABLE 14. DIFFERENCES BETWEEN UN 1.4G AND CANADIAN 7.2.1

	United Nations 1.4G	Canada 7.2.1
Pre-loaded mortars / Shot tubes	Internal diameter ≤ 30 mm Total pyrotechnic composition ≤ 25 g Flash powder ≤ 5%	Internal diameter ≤ 50 mm Total pyrotechnic composition ≤ 50 g Flash powder ≤ 800 mg
Roman candles	Internal diameter ≤ 30 mm Each pyrotechnic unit ≤ 25 g	Internal diameter ≤ 22 mm Total pyrotechnic composition ≤ 40 g Number of pyrotechnic units ≥ 5
Mines	Total pyrotechnic composition ≤ 150 g Each pyrotechnic unit ≤ 25 g Flash powder ≤ 5%	Total pyrotechnic composition ≤ 40 g Flash powder ≤ 1 g

Classification of Fireworks in the United Kingdom

In accordance with the Classification and Labeling of Explosives Regulations (CLER), the UK Competent Authority (CA) must classify explosive materials prior to their storage, distribution or transportation. The Health and Safety Executive (HSE) is the relevant CA for commercial explosives. Fireworks classification options for the HSE include:

1. Use the UN serial number, hazard code and compatibility group based upon UN test series data

2. Classify by analogy with a similar product previously classified by HSE.

3. Classification by default (only subtle variations from UN default method)[*]

In an effort to also address special hazards related to storage and manufacturing conditions not covered by the UN scheme, the HSE devised a structure of hazard types. These special conditions, which HSE concluded were not addressed by the UN scheme, were based upon lessons learned from explosions at manufacturing / storage facilities in the United Kingdom and The Netherlands involving highly energetic pyrotechnic materials (not UN class 1.4G fireworks). However, as previously discussed, experimental results of the combustion of large amounts of star shells within steel ISO transport containers may illustrate the potential for similar hazards from certain 1.4G devices. Therefore, in order to address such special issues, the hazard type scheme was developed[56]. Table 15 presents the criteria for Hazard Type 4, which would be most relevant to the scope of this review.

TABLE 15. CRITERIA FOR UK HAZARD TYPE 4

Hazard Type 4 - Having a fire or slight explosion hazard or both, with only local effect	
Airbomb	Internal diameter < 30 mm
Battery	Gross mass < 10 kg
Combination	Gross mass < 10 kg
Fountain / Gerb	< 8 oz or 26 mm calibre
Lancework	Simple lancework or lancework containing fireworks of Hazard Type 4
Mine	Internal diameter < 100 mm
Rocket	< 4 oz calibre or 25 mm diameter
Roman Candle	Internal diameter < 30 mm and not including bombettes containing flash compositions
Wheel	Gross mass < 1.5 kg (excluding frame)
Selection Boxes	Containing only types of Hazard Type 4
Any items of UN HD 1.4	As classified by HSE under CLER and not otherwise placed in Hazard Types 1 or 3

As further guidance to the implementation of the data in Table 14, users are directed that "*all shells classified as UN HD 1.4 are considered Hazard Type 3 unless they are stored in accordance with the following conditions, in which case they may be considered to be Hazard Type 4:*

1. *They are kept in their closed transport packages*
2. *Within the container the storage of shells is limited to units or stacks holding a maximum number of 8 boxes of shells in each*
3. *Shell units/stacks shall be separated from each other in any direction by either a:*
    a. *1 m air gap or barrier of empty boxes or boxes with low energy fireworks*
    b. *0.5 m barrier of boxes filled with sawdust or similar material.'*[69]

One of the most significant features of this hazard type scheme is the consideration of the effects of material packaging. It is thought that for highly energetic materials, this additional fuel mass, which mutually insulates adjacent commodities, actually slows the speed of flame propagation thereby turning a potential detonation into a mere rapid expansion of gases (explosion). Ultimately, more research in this area is needed.

Classification of Fireworks in Japan

In Japan, the population of devices including highway flares, model rocket engines and consumer fireworks is more commonly referred to as toy fireworks, a name which certainly implies a low hazard severity. A total of 34 additional subcategories are used to further differentiate toy fireworks on the basis of output and composition. A limit of 15 grams low explosive composition is applied as a maximum for toy fireworks in the country. The Bureau of Pyrotechnics Inspection (BPI), a division of Japan Pyrotechnics Association (JPA), is the agency responsible for the inspection of toy fireworks purchased in the country. The Ministry of Economy, Trade and Industry (METI) provides government authorization to JPA. It is notable that approximately 80% by volume of Japanese fireworks are imported. The majority of these imports are reportedly Chinese[57].

RELEVANT CODE PROVISIONS FROM OTHER (INTERNATIONAL) CODES

Historically, the development of regulations regarding the safety and serviceability of buildings and structures in America has fundamentally differed from the same process in other countries. This fundamental difference was the lack of oversight by the federal government on the development and enforcement of a single code. Instead, this responsibility was left to the private sector. The result was the establishment of multiple model building codes governing different regions of the country. In 1994, the private enterprises responsible for maintaining these model codes joined to form the International Code Council with the intent of creating consensus regulations. Although the International Codes have been adopted as the basis for regulating building safety and serviceability in nearly every state, local amendments to the codes have promoted the survival of regional differences. For the purpose of this analysis, only the foundational documents (International Codes) are analyzed with respect to applicable provisions. The most relevant of these codes are the 2006 (current) edition of the International Building and International Fire Codes, respectively.

2006 International Building Code (IBC)

In addition to the provisions of the International Fire Code (IFC), irrespective of material quantity beyond a critical amount, any building or structure utilizing hazardous materials is required to comply with IBC Sections 307 *High-Hazard Group H*, 414 *Hazardous Materials* and 415 *Groups H-1, H-2, H-3, H-4 and H-5*.

The purpose of identifying hazardous occupancies is to recognize the relatively high degree of hazard posed by the chemical properties of materials on the premises. Identification of such materials is made specifically on the basis of information from NFPA standards and the Code of Federal Regulations (DOL 29 CFR). Generally speaking, objectives focus on isolation of storage and industrial operations while typically providing additional systems or elements of protection. The intent of the code is to provide these elements of protection despite the relatively low anticipated occupant load. This is done to account for the hazard posed to the surrounding area[58].

High-Hazard Group H occupancies include, among others, the use of a building or structure, or a portion thereof that involves the manufacturing, processing, generation or storage of materials that constitute a physical or health hazard in quantities in excess of those allowed in control areas constructed and located as required in Section 414. The concept of a control area is to concentrate the location of hazardous materials (with quantity limits) in a single area bounded on all sides by some combination of fire barriers, horizontal assemblies, fire walls and exterior walls.

Hazardous uses are classified in Groups H-1, H-2, H-3, H-4 and H-5 with the last group reserved for hazardous material production facilities. Exceptions are provided for conditions including building construction and use, packaging of materials, quantity of materials, or fire protection measures, which warrant exemption from classification as a hazardous use group. When these exceptions apply, although classification as a hazardous use group is not necessary, compliance with IBC Section 414 and the International Fire Code is still required.

A tabulation of material quantity limitations for control areas is given in IBC Table 307.1(1) *Maximum Allowable Quantity Per Control Area of Hazardous Materials Posing a Physical Hazard*. If any material exceeds these limitations, the entire building in question must be classified as a high-hazard occupancy. Consumer fireworks are specifically identified in this table in terms of UN classification 1.4G with an assigned limit of 125 solid pounds. However, two distinct opportunities are presented for an increase in this quantity limit. The first is an increase of 100 percent per control area when an automatic sprinkler system designed in accordance with NFPA 13 *Standard for the Installation of Sprinkler Systems* is provided. The second is also an increase of 100 percent per control area when the fireworks are stored in approved storage cabinets, day boxes, gas cabinets, exhausted enclosures or safety cans. In the event that both of these measures are taken, a total additive increase of 200 percent may be applied to the net weight of pyrotechnic composition. If this value is not known, the code specifically requires the use of 25 percent of the gross weight of the fireworks, including packaging, as the basis for evaluation. If the established quantity limit is exceeded, the entire building must be classified as a Group H, Division 3 occupancy in accordance with Table 307.1(1). Note that in such a case, IBC Section 903.2 would require an automatic sprinkler system in accordance with NFPA 13.

IBC Section 414 *Hazardous Materials* provides special requirements for control areas. When control areas are used, the thermal integrity of their construction must be a minimum of 1-hour fire barrier wall construction or 2-hour if the building is more than 3 stories in height. Floor construction is generally required to be of 2-hour fire-resistance rated construction. An exception to this general rule is the case where a building of Type IIA, IIIA or VA construction, which is less than 4 stories in height, is provided with an automatic sprinkler system. In this case, the floor construction is permitted to have a 1-hour fire-resistance rating. In situations where multiple control areas are designed for the same building, limitations are placed upon both the number of control areas per specific floor of the building and the maximum percentage of allowable material quantities per control area. These limits generally allow decreasing amounts of hazardous materials as the distance both above and below grade plane is increased. The intent of this trend is in part to assist fire department personnel[70].

IBC Section 415 provides specific requirements for each of the 5 subdivisions of the Group H occupancy type. With regard to consumer fireworks, these requirements are applicable when control areas are not used and the facility is consequently classified as a Group H, Division 3 occupancy. One of the most important design requirements addressed in this section is the issue of fire separation distance. For Groups H-2 and H-3 occupancies, exterior walls must comprise a minimum of 25 percent of the perimeter wall of the occupancy. No exceptions to this rule are applicable to consumer fireworks. Additionally, the minimum fire separation distance for the building as a whole is governed by IBC Section 415.3.1, which requires separation of Group H-3 occupancies in accordance with the International Fire Code. The basis of these separation distances in the IFC is a quantity-distance method. Distances are measured from the walls enclosing to occupancy to lot lines, including those on a public way.

Detached storage is required by IBC Table 415.3.2 for Division 1.4 explosives (includes consumer fireworks) when the maximum allowable quantity is exceeded. When detached storage is required, there are no requirements for wall and opening protection based on fire separation distance. When the maximum allowable quantity per control area is exceeded, the Group H-3 occupancy is required to be within a building used for no other purpose, which does not exceed 1 story in height and is without basements, crawl spaces or under-floor spaces (IBC Section 415.5).

Requirements for means of egress specific to Group H, Division 3 occupancies are found in IBC Chapter 10. One of the primary considerations in applying egress related requirements is the determination of an occupant load. IBC Table 1004.1.1 provides a list of occupant loads as a function of the intended use of the area in question. Although no specific mention is made of facilities focused on the retail sale and storage of consumer fireworks, general industrial areas are listed at an occupant load of 100 square feet of gross floor area per occupant. This figure corresponds with the occupant load listed in NFPA 101 *Life Safety Code* for general and high hazard industrial use. This value may be accurate for storage facilities; however, it seems that a more realistic number for retail facilities, particularly during peak season, would likely correspond to mercantile use. The occupant load for the grade floor of a mercantile facility is given as 30 square feet of gross floor area per occupant both by IBC Table 1004.1.1 and NFPA 101. In an effort to lend a realistic context to this estimate, consider that the Ohio River Fireworks store in Scottown, Ohio was loaded at approximately 20 square feet of gross floor area per occupant at the time of the fatal fire in 1996. This suggests a need for further analysis in this area.

Factors for egress width per occupant served are given in IBC Table 1005.1. For Group H, Division 3 occupancies equipped with an automatic sprinkler system in accordance with NFPA 13, all egress components other than stairways must have a minimum width of 0.2 inches per occupant.

A minimum of two exits or exit access doorways are required for Group H, Division 3 occupancies with a maximum height of 1 story above grade plane where the occupant load is greater than 3 or the common path of egress travel exceeds 25 feet (IBC Section 1015.1). This is the maximum common path of egress travel allowed by IBC Section 1014.3 for Group H, Division 3 occupancies. The minimum required separation distance between exits for a building with an NFPA 13 automatic sprinkler system is one-third of the length of the maximum overall diagonal dimension of the area served. The maximum travel distance for this same condition is 150 feet (IBC Table 1016.1).

2006 International Fire Code (IFC)

Chapter 33 of the IFC *Explosives and Fireworks* is dedicated to governing the possession, manufacture, storage, handling, sale and use of explosives, explosive materials, fireworks and small arms ammunition. IFC Section 3301.1.3 states that the possession, manufacture, storage sale, handling and use of fireworks are prohibited except for the following cases:

1. Storage and handling of fireworks as allowed in IFC Section 3304

2. Manufacture, assembly and testing of fireworks as allowed in IFC Section 3305

3. The use of fireworks for display as allowed in Section 3308

4. The possession, storage, sale, handling and use of specific types of Division 1.4G fireworks where allowed by applicable laws, ordinances and regulations, provided such fireworks comply with, Consumer Product Safety Commission (CPSC) 16 CFR, Parts 1500 and 1507, and DOT 49 CFR, Parts 100-178, for consumer fireworks (See Appendix A for individual state laws).

In addition to these requirements, IFC Section 3301.2.2 prohibits the sale and retail display of fireworks upon highways, sidewalks, public property or in Assembly (Group A) or Educational (Group E) occupancies.

Separation distances involving the relative positioning of storage magazines, the operating building, inhabited buildings and public traffic routes are calculated in accordance with a number of methods as referenced in Table 3301.8.1(3) (Table 16 in this report). Note that the required minimum separation distance is 50 feet in all cases and that linear interpolation between tabular values is not allowed. Prior to presenting this table, it is important to define the methods referenced. These are as follows from IFC Section 3302.1:

1. Intraline distance (ILD) or Intraplant distance (IPD) is the distance maintained between any two operating buildings on an explosives manufacturing site when at least one contains or is designed to contain explosives, or the distance between a magazine and an operating building (does not apply to retail sale and storage of consumer fireworks, but is presented for clarity in conjunction with Table 15).

2. Inhabited building distance (IBD) is the minimum separation distance between an operating building or magazine containing explosive materials and an inhabited building or site boundary.

3. Intermagazine distance (IMD) is the minimum separation distance between magazines.

4. Public traffic route (PTR) is any public street, road, highway, navigable stream or passenger railroad that is used for through traffic by the general public.

TABLE 16. IFC TABLE 3301.8.1(3) APPLICATION OF SEPARATION DISTANCES

Item	Magazine	Q-D	Operating Building	Q-D	Inhabited Building	Q-D	PTR	Q-D
Magazine	See Table 16 [IFC Table 3304.5.2(3)]	IMD	See Table 16 [IFC Table 3304.5.2(3)]	ILD or IPD	See Table 16 [IFC Table 3304.5.2(3)]	IBD	See Table 16 [IFC Table 3304.5.2(3)]	PTR
Operating Building	See Table 16 [IFC Table 3304.5.2(3)]	ILD or IPD	See Table 16 [IFC Table 3304.5.2(3)]	ILD or IPD	See Table 16 [IFC Table 3304.5.2(3)]	IBD	See Table 16 [IFC Table 3304.5.2(3)]	PTR
Inhabited Building	See Table 16 [IFC Table 3304.5.2(3)]	IBD	See Table 16 [IFC Table 3304.5.2(3)]	IBD	NA	NA	NA	NA
PTR	See Table 16 [IFC Table 3304.5.2(3)]	PTR	See Table 16 [IFC Table 3304.5.2(3)]	PTR	NA	NA	NA	NA

Division 1.4 explosives are recognized by IFC Section 3301.8.1.4 as having a moderate fire but no blast hazard. For that reason, they are assessed in a different manner than other subdivisions of explosives. In determining setback distances for Division 1.4 explosives, the total weight of the explosive material is used in determining required setback distances as shown in Table 17 of this report (IFC Table 3304.5.2(3)). Where two or more magazines are separated from each other by less than the IMD, such magazines as a group must be considered as one magazine and the total quantity of explosive materials stored in the group shall be treated as if stored in a single magazine. The location of the group of magazines must comply with the IMD specified from other magazines or magazine groups, inhabited buildings

(IBD), public transportation routes (PTR) and operating buildings (ILD or IPD) as required (IFC Section 3304.5.2.2).

TABLE 17. IFC TABLE 3304.5.2(3) TABLE OF DISTANCES

Quantity of Division 1.4 Explosives		Distances [ft]			
Pounds over	**Pounds not over**	**IBD**	**PTR**	**IMD**	**ILD or IPD**
50	Not Limited	100	100	50[a,b]	50[a]

Notes:

a. A separation distance of 100 feet is required for buildings of other than Types I or II construction as defined in the IBC.

b. For earth covered magazines, no specified separation is required.

The remainder of provisions in the IFC relevant to the retail sale and storage of consumer fireworks are divided into requirements for construction, operation, maintenance, inspection and disposal of explosive materials. Requirements for construction in Section 3304.6 detail drainage, heating, lighting, the use of non-sparking materials and provision of signs and placards. Requirements for maintenance include housekeeping and repair procedures.

Regulations of the International Community

The provisions of the International Codes are useful for analysis of requirements in the United States; however, the vast majority of other countries around the world do not use these codes as a basis for regulation and enforcement. In 2003, an effort was made by the UK Health and Safety Laboratory to accumulate and analyze control systems for the storage of fireworks in several countries[59]. The objectives of this effort did not focus entirely on consumer fireworks and as a result, information on topics such as evaluation of accidental ignition, the use of TNT-Equivalence and Net Explosive Quantity (NEQ) are not discussed here.

Regulating setback distances for facilities, inhabited buildings, storage magazines and the like is prescribed as a function of the quantity of materials present. Such methods, which are commonly referred to as quantity-distance schemes, are known to be common to the United States (as discussed above), Great Britain, Australia, Sweden, Switzerland, France, Germany, Malta and Canada. However, specifics of the method between countries contain some variations. For instance, in Queensland, Australia, these distances are design guidelines for a risk-based analysis as opposed to mandatory requirements. Similar degrees of freedom exist in Great Britain where a license application from a retail store may result in a less strict interpretation from the HSE. In Malta, quantity-distance schemes are used for military and industrial explosives but not for fireworks. The Swiss specify distances as a function of quantity, which are entirely independent of the type of explosives stored. In addition, they allow essentially unlimited quantities of explosives to be stored in magazines with amounts on the order of 25 kg kept in lockers in unoccupied rooms at grade level or in work-yards. The Germans specify off-site separation distances based upon qualitative evaluations of the exposed areas.

Several of these countries, except for Sweden and Malta, allow the storage of what they define as small quantities of explosives not falling under the requirements of quantity-distance methods of separation. The definition of small quantities varies from as little as 20 kg in France to 150 kg in Western Australia. In Switzerland, storage related to consumer retail facilities specifically within the context of sales for the national festival on August 1st or the New Year's Eve celebration are exempt from the quantity-distance method of separation[59].

The UN scheme for classifying explosives is dependent on material packaging. Once this packaging is removed or perhaps altered in a significant way, the resulting classification may also change. For instance, the issue of confinement for large quantities of materials stored in steel freight containers may warrant a change in classification due to increased hazards. This factor is specifically recognized by Sweden, Switzerland, Germany, the United States and Great Britain with variations on the method of resolution[59].

In France, Germany, Australia, Canada and Sweden, the UN classification is a factor in determining the maximum allowable material quantities for storage. The French take into consideration the total mass of material as well as the projection distance in further classifying fireworks for the purpose of storage. A similar method is employed by the Germans who subdivide fireworks into an additional layer of four classes distinguished primarily by pyrotechnic mass. Both nations utilize quantity-distance schemes based upon the UN classifications. Great Britain utilizes the hazard type concept presented in the hazard data section of this report. One of the most unique practices in classification is found in Sweden in which fireworks sold to consumers are classified as Division 1.3 due to the removal of cardboard packaging. Consideration of packaging on a much larger scale is made by both France and Canada where the hazard division is a function of the confinement within the facility. Classification of mixed fireworks corresponds to the most hazardous type in Great Britain, France, Germany and Australia[59].

The construction type of an explosives storage facility is specifically regulated in Germany, Australia, and the United States. In the U.S., this is done in part to protect against sensitivity to the mechanical impact of bullets. In Australia, the purpose is generally to provide increased security. Environmental considerations are most evident in Australian regulations which allow any local authority to modify the requirements of the Explosives Act such that this issue is addressed in a performance-based manner[59]. Appendix B includes copies of legislation in Great Britain, Australia, Canada and Malta which are significant to the context of this work.

RELEVANT CODE PROVISIONS FOR ANALOGOUS HAZARDOUS COMMODITIES

An evaluation of the hazards related to fire protection for consumer fireworks may be assisted by an analysis of similar hazardous commodities. The first step in creating a rigorous engineering solution to a complex problem is the identification of objectives based upon hazard dependent variables. In this case, the challenge at hand is the production of feasible fire protection objectives related to the fundamental combustion process and the effects imposed on the surrounding enclosure. Based upon the preceding analysis of loss history in conjunction with relevant physics, chemistry and engineering principles, the following hazard dependent variables are highlighted for comparison in Table 18.

1. Fundamental commodity hazards
2. Influence of storage / packaging on fundamental hazards
3. Fire prevention and control
4. Output (maximum anticipated severity in the event of a fire)

TABLE 18. CONCEPTUAL COMPARISON OF ANALOGOUS HAZARDS

	Oxidizers (NFPA 430)	Aerosols (NFPA 30B)	Flammable & Combustible Liquids (NFPA 30)	Organic Peroxides (NFPA 432)
Fundamental commodity hazards	Increase reaction rate and ignition potential of surrounding materials. Release of toxic gases such as chlorine	Rupture of cans produces fireball Projectile hazard Residual pool fire Smoke quantity and toxicity	Wide range of flash points, ignition temps Evaporation of a spill, ignition of vapors Electrostatic ignition Spray Fires Containment BLEVE Radiation and toxicity	Initiation of explosive material polymerization High heat release rate Toxicity of gases Chemical instability Ease of ignition Highly reactive with diverse material types
Storage Arrangement and Quantity	Aisle access for FD, housekeeping Area marked for most severe hazard class. Geometry & quantity are function of hazard class, container type, storage type and fire protection provided.	Aisle access for FD, housekeeping Area marked for most severe hazard class. Geometry & quantity are function of hazard class, packaging, ceiling height, storage height and fire protection provided.	Aisle access for FD, housekeeping Area marked for most severe hazard class. Geometry & quantity function of hazard class, container type, storage location, occupancy type, ceiling:storage height, FP provided	Aisle access for FD, housekeeping, reactivity Max quantity for mixed storage is by proportion Geometry & quantity are function of hazard class, storage type and fire protection provided.
Fire Prevention Measures	Training program required for personnel Maintenance operations supervised. Smoking prohibited. Design so storage can't contact heating units, piping, ducts. Mandatory housekeeping	Only trained operators of industrial trucks Control ignition sources (smoking, open flame) Segregation of aerosol in waste disposal Written preventative maintenance program Static electricity dissipation system	Personnel training, emergency action plan Control ignition sources Safe tank disposal Tank protection from trespassing/vandalism Tank overfill protection Regular insp., maint. Static electricity dissipation methods	Personnel training handling, use, safety Limit switches for storage temperatures Control ignition sources (no smoking) Supervised maintenance Regular housekeeping prevent contact w/pipes, heating units, etc
Output (Maximum anticipated severity from loss history and testing)	Limited potential for life loss, occupant load low. Destruction of entire storage warehouses FD resources: 5 Alarm fire, 24 hour effot Environmental hazard - water runoff, gases	Potential for life loss - higher occupant loads Destruction of entire storage warehouses FD resources: 1 week effort in Falls Township Environmental hazard - water runoff, gases	$97M - lighting strikes tanker & 80,000 bbl ethanol tank (TX, 1979)[41] Destruction of storage facility & surroundings FD: significant efforts Environmental hazard - water runoff, gases	Occupant load low, public exposure high? Destruction of storage facility & surroundings FD: explosive incident time < response time? Environmental hazard - water/chemical runoff
Protection Objectives Specific to Combustion	Commodity specific Segregate commodity Noncombustible building construction Copious water spray with fuel access is heat sink Limit additional adverse chemical reactivity.	Occupancy specific: manufacturing, storage, retail uses Segregate commodity Early delivery of water, high droplet momentum Robust fire wall barriers, limit openings	Containment specific: tank, piping system, container/portable tank Pressure relief venting Separation distances Droplet momentum, foam blanketing Spill, boilover control	Containment specific: segregated, cut-off, detached storage High droplet momentum Storage temperatures Segregate commodity Fire barriers and separation distances
Protection Objectives Specific to Effects of Combustion	No mention of detection / notification. No mention of egress route and capacity. Venting of gaseous products not required Fire department access - water supply	Fire alarm systems provided per NFPA 72, gas detection Means of egress NFPA 101 compliant Ventilation in manufacturing facilities Fire department access - water supply	No specific reference to heat/smoke detection, gas detection utilized Means of egress NFPA 101 compliant Ventilation for inside rooms, warehouses Fire department access - supply of agent used for fire control	No mention of detection / notification No reference to NFPA 101, unoccupied spaces No mention of ventilation for storage facilities Liquid-tight construction Fire department access-supply of agent

The manner of approach is therefore similar to a mathematical function. Recognizing that the most powerful functions are those, which are widely applicable, it is most logical to compare hazards and corresponding protection strategies on a general conceptual level. Based on the general overview presented, an acceptable level of risk associated with the protection of certain commodities may be inferred. As discussed regarding control mechanisms for consumer fireworks around the world, the determination of the level of acceptable risk is often subjective thereby introducing society itself as a significant variable in the process. This particular comparison focuses only on existing NFPA standards, which are most commonly used and developed within the United States.

The manner and extent to which the commodities chosen for comparison in Table 18 are similar to consumer fireworks both vary. There are indeed many material properties that differ significantly from fireworks. For example, consider that the fundamental process of combustion for metal powder fuels used in fireworks is heterogeneous, while that of flammable and combustible liquids is homogeneous (single phase). This results in a vastly different solution structure for the chemical kinetics driving the process. The utility of this presentation is the examination of how dynamics such as flame spread and projectile behavior are generally managed in existing NFPA standards. This comparison is also made within the context of loss history, which is recognized as a significant motivation for the development and validation of protection strategies.

Fundamental Commodity Hazards

Based upon the brief loss history and experimental testing discussed in this report, the fundamental commodity hazards with respect to consumer fireworks appear to be primarily related to the speed of hazard development. These tests showed how the combustion of metals with prepackaged oxidizers can produce gas temperatures within an enclosure that locally exceed the range of a ventilation limited fire. These high temperatures associated with metal combustion also resulted in rapid deformation of the storage unit during the Battelle tests. The result was commodity burning in the aisles. In addition, the rapid development observed particularly during the experimental program by Battelle illustrated how the projectile behavior of some devices can influence fire spread across relatively wide aisles. This supports current provisions in NFPA 1124 intended to limit projectile behavior of aerial devices.

Fire protection standards for these analogous commodities provide a conceptual reference for feasible protection strategies. In the case of aerosols, material segregation and passive barriers are utilized to contain the projectile hazard to a certain area. For oxidizers, a high rate of heat absorption from automatic sprinkler protection is desired. As a result, in-rack sprinklers are commonly specified in rack storage applications in order to provide clear water access. Additionally, horizontal fire barriers are installed at every tier and vertical barriers provided at all rack uprights to confine the fire area. This is a common approach for retail storage of oxidizers. Based upon the results of the Battelle testing, further research may be necessary to evaluate whether more thermally robust methods of storage than gondola shelving should be explored (i.e., rack storage). Additionally, potential shielding of the commodity is an area of interest for determining whether in-rack sprinkler protection would be necessary for such a situation.

Storage Arrangement and Quantity

The concept of storage arrangement and material quantity influencing the hazard severity of a fuel commodity is not unique to fireworks. The following examples describe the effects of storage arrangement and material quantity for a number of other applications[41]. The list of issues is by no means exhaustive. It is most useful here in establishing a basis for the investigation of the general influences of material packaging, relative storage arrangement and the effects of the larger enclosure (surrounding containment structure).

1. Storage of a flammable or combustible liquid must be within a tank or container that is both thermally and mechanically robust in order to prevent the increased hazard to the surroundings resulting from a liquid spill.

2. Reactive materials such as oxidizers and organic peroxides must be segregated from incompatible materials during storage.

3. Aerosols must be segregated from surrounding fuel commodities due in part to the projectile hazard of the product, which is a mechanism for fire spread across relatively large distances. The projectile distance is a function of the commodity vapor pressure and the can strength. The resulting spot fire will burn with the characteristics of the flammable / combustible liquid within the container.

4. The decrease in exposed fuel surface area and restricted interior airflow resulting from typical solid piled storage arrangements significantly influence the burning rate of the fundamental commodity.

5. Palletized storage of commodities in which boxes are stacked atop wooden pallets, allows for increased air access in the horizontal plane underneath the commodity. This increased degree of air access is also significant in rack storage applications. However, in rack storage, additional fuel surface area along the top surface of the commodity is also exposed on each tier.

6. Fire growth within either a palletized or solid piled storage array is heavily dependent on the exposed surface area of the vertical fuel surfaces in the array.

7. In multiple-row rack storage applications, the relatively narrow spacing between adjacent rows often facilitates fire spread.

8. The maximum heat release rate for the standard plastic commodity has been found to be directly proportional to the number of storage tiers. Furthermore, the characteristic increase in the flow momentum suggests a necessary increase in droplet momentum from overhead sprinklers.

9. The ratio of storage height to ceiling height is known to influence the burning rate of stored commodities by enhancing thermal feedback from the enclosure to the solid fuel surfaces below.

10. Fire spread between adjacent storage aisles is a function of radiant heat transfer, which may be mitigated by establishing sufficient separation distances.

11. Encapsulation of a standard commodity in plastic shrink-wrapping may increase the hazard severity of the commodity when significant amounts of plastic are introduced.

Many of the storage hazards described above relate in increase in hazard severity to an increased degree of air access to the fuel commodity. In the case of consumer fireworks, the fuel and oxidizer are pre-packaged elements of the commodity. Consequently, the same principles would not directly apply. However, as previously discussed, the cardboard packaging of these devices has been recorded as dominating the earliest stages of fire development in certain cases. The concepts of air access are certainly applicable to the burning packaging and may ultimately be useful in achieving early fire control.

Fire Prevention Measures

Fire prevention is often accomplished by controlling or eliminating ignition sources via the following safe practices.

1. Smoking is prohibited in proximity to the hazard.

2. Maintenance operations such as cutting and welding are conducted in accordance with standardized safety procedures and supervised.

3. Containment facilities are grounded in a static electricity dissipation system.

4. Housekeeping is conducted regularly such that excess combustibles or reactive materials are properly organized and/or disposed.

5. Elements of necessary building systems such as piping and ductwork serving heating units are designed in a manner such that the potential for contact with the stored commodity is minimized.

6. Facility personnel are required to be trained in the operation of fire protection equipment and the execution of a documented fire safety/emergency response plan.

7. Facilities are required to be secured in a manner that prevents trespassing, vandalism or handling of materials by untrained personnel.

In addition to these practices, further hazard specific measures may be taken in response to lessons learned from prior loss history. Such measures include the installation of limit switches to prevent overflow of flammable and combustible liquid storage tanks or to keep temperatures within a certain range in organic peroxide storage units. In the case of aerosols, the major loss at the *K Mart* facility in Falls Township prompted the stipulation in NFPA 30B that industrial lift trucks may only be operated by trained personnel. Perhaps in the case of consumer fireworks, increased security or indirect customer access to the commodity might be a feasible response to the arson that occurred in Scottown, Ohio. However, it is important to note that NFPA 1124 was not in existence at the time of this tragedy. Additionally, no significant loss-history has been documented since the genesis of the standard.

Flammable and combustible liquids provide perhaps the most prominent example of a commodity that is regulated on the basis of material sensitivity. These liquids are categorized into hazard classes according to ignitability properties. This is in contrast to many product classification schemes such as aerosols, oxidizers, organic peroxides and explosive materials that are dependent primarily upon material output. Ultimately, the most complete method of classification should take both factors into account simultaneously rather than favoring one over another. This is particularly true of consumer fireworks, which are already categorized in terms of a relatively minimal output within the domain of explosive materials.

Output

Aside from the flammable and combustible liquids example, fire protection standards typically classify hazard severity in terms of energy output. This output may be expressed qualitatively as in the case of oxidizers or quantitatively as in the case of aerosols with specific loss history contributing valuable information. Table 18 provides a qualitative comparison of risks associated with loss of life, property damage, required fire department resources and environmental hazards. Each of these event outcome parameters is the result of the power of the chemical reaction and the speed at which it spreads and develops with respect to the response of active fire protection.

The infamous fire in Falls Township involving aerosol commodities is an excellent example of how these factors are interwoven into a final assessment of output. Among the most significant factors contributing to the devastation caused by this event was the speed of its far-reaching development. This was due to the inherent mobility of the flammable liquid hazard as a projectile. Not only did these projectiles quickly enhance fire spread by igniting a series of spot fires, but they also served as a safety hazard for firefighters staging an interior attack.

The time for the hazard to reach full power and create maximum devastation is an even more significant factor in the case of organic peroxides and Boiling Liquid Expanding Vapor Explosions (BLEVE). In these cases, the devastation may occur at a speed and magnitude that threatens the relevance of manual firefighting provisions or even more reliable and responsive methods of automatic protection. Furthermore, the magnitude of the event may threaten the population in a surrounding area despite a low occupant within the facility itself. For consumer fireworks this level of enhancement is not expected. However, a combination of experiments (Washington and Battelle) and loss history (Scottown, Ohio) indicate that the most severe stages of the enclosure fire may take place prior to the arrival of the fire department. Further research is necessary to confidently address the utility of automatic sprinkler protection for this application.

Protection Objectives Specific to Combustion

Safety objectives related specifically to the combustion process are related to either fire suppression or fire control. Suppression may be achieved by a combination of automatic and manual means once a suitable type of agent and rate of application is determined. In addition to the rate of application, characteristics such as water droplet distribution, size and trajectory are significant in evaluating the protection efficiency. In the case of oxidizers, a very high rate of water application is necessary in order to produce the required heat sink effect. Additionally, it is desirable to disrupt the storage configuration and increase the area over which energy is transferred directly to the water. For aerosols, the key to automatic protection is fast and aggressive response resulting in early suppression. Several other fire protection tools have also proven quite effective for fire control where hazardous or potentially hazardous materials are stored. Among these tools are fire barrier walls interior to a storage array for containment as well as commodity separation distances.

Protection Objectives Specific to Combustion Effects

The effects of combustion are most plainly manifested in the evolution of tenability within the area of fire origin. The challenges presented by an enclosure with decreasing tenability over time are generally similar over a wide range of occupancy types and commodity hazards. In general, the most pertinent fire protection objectives begin with detection of the incident. Depending on the type of hazard, this may involve detection of smoke, heat or additional hazardous gases. Once detection is accomplished, occupant notification to initiate egress and the implementation of any automatic safety features such as smoke control / ventilation may be performed. Table 18 implies that the provision of automatic detection and occupant notification features is a function of the occupant load of the facility. It seems that such features would be appropriate for consumer fireworks retail facilities, which experience relatively large occupant loads during the peak sales season. Along these same lines, the provision of smoke control in the form of ventilation is typically done as a means of providing tenable conditions or facilitating fire department overhaul procedures. In the case of single story facilities, the provision of ample egress capacity may alleviate the need for such features. In addition to these considerations, provisions for fire department access such as access to the commodity via aisle spacing and the provision of tools such as standpipes and fire hydrants may be necessary.

CONCLUSIONS

Chapters 6 and 7 of the 2006 edition of NFPA 1124 Code for the Manufacture, Transportation, Storage and Retail Sales of Fireworks and Pyrotechnic Articles provide requirements for storage and retail sales of consumer fireworks. This section of the report explores these sections as they currently exist in the standard and analyzes significant requirements with respect to the previous information gathered in the literature review. The objective of this approach is to identify and analyze areas of the standard that could benefit from focused research in light of the preceding literature review.

NFPA 1124 Provisions for Storage of Consumer Fireworks

The scope of these requirements specifically apply to consumer fireworks, which the standard defines as assembled devices that have been approved by the Department of Transportation as Fireworks UN0336 and Articles, Pyrotechnic UN0431 and UN0432. It is important to note that although the mission of NFPA as an organization includes a worldwide perspective on fire related hazards, this definition implies that the applicability of this section of the standard is limited to the United States (i.e., reference to the DOT). Specifically, the storage requirements are meant to apply to both permanent and temporary buildings where the net weight of pyrotechnic content exceeds 125 pounds (250 pounds if equipped with an NFPA 13 automatic sprinkler system). It is recommended that careful consideration be given to this automatic sprinkler tradeoff given that significantly more research is needed to evaluate the effectiveness of the breadth of sprinkler system types allowed by NFPA 13 (i.e., dry pipe, wet pipe, ESFR, etc.). More work should be done in this area to support such a general tradeoff.

Construction materials are permitted without limitation for buildings with a floor area not greater than 8,000 ft^2. The basis for selecting this critical area is unclear. As currently written, the standard would allow for the same showroom used in the test to be of unprotected construction.

Further research regarding the balance between fuel loading, sprinkler protection and structural protection is necessary before such specific criteria can be reasonably implemented.

A number of fire protection strategies are given for automatic sprinkler systems in Section 6.5.1 of the standard. These options include the following:

- Consumer fireworks stored in DOT-approved packaging shall be considered as a Class IV commodity.
- Consumer fireworks stored to a height not greater than 10 ft in racks or 12 ft otherwise shall be classified as an Ordinary Hazard (Group 2) occupancy.
- Consumer fireworks stored to a height not greater than 12 ft in racks, but greater than 10 ft shall be classified as Extra Hazard (Group 1) occupancy.
- Consumer fireworks stored to a height greater than 12 ft shall be protected by an automatic sprinkler system designed using a fire control approach or a special design approach in accordance with NFPA 13, Standard for the Installation of Sprinkler Systems.

Based upon the research explored in this literature review, there appears to be no basis for any of these very specific design requirements. If data exists which suggests that consumer fireworks stored in DOT-approved packaging exhibit similar burning behavior to a Class IV commodity, then it should be referenced in the standard so that the basis for this requirement is clear. Similarly, the rationale for using requirements related to occupancy classification on the basis of storage height should be detailed in the appendix of the standard. If further testing is necessary for such justification, this testing should be performed or the specific requirements removed from the standard. Currently, it appears that sprinkler protection is provided based solely upon the hazard posed by packaging; however, supporting data for this strategy is inadequate at best.

Smoke and heat vents are required by Section 6.5.3 for consumer fireworks storage buildings exceeding 50,000 ft^2 in undivided area. The author of this review was unable to locate any data for consumer fireworks fire related hazards in the built environment in spaces of this size. Additionally, smoke and heat venting was not a strategy employed in any of the known experimental efforts involving fire in consumer fireworks storage facilities.

Means of egress are referenced in Section 6.8 and required to comply with NFPA 101, Life Safety Code. However, coordination with the Life Safety Code requires identification of an occupancy type as well as the relative hazard level of contents. Specific guidance on this issue is sparse. As a result, there is a certain level of ambiguity associated with judging compliance with NFPA 101. Requirements are provided in NFPA 1124 with respect to doors, aisles, egress travel distance, exit signs and emergency lighting; however, the basis for these requirements (particularly aisles and travel distance) is unclear.

NFPA 1124 Provisions for Retail Sales of Consumer Fireworks

The requirements for retail sales of consumer fireworks contained in Chapter 7 of the standard apply to both permanent and temporary facilities including stores, stands, tents, canopies and membrane structures. Criteria for exempt amounts recognizes the value of the preventative function of packaging by specifying that fireworks must be in packages in addition to limiting the total amount of pyrotechnic composition. Similar to requirements for storage, limits are set at

125 pounds (net) or 250 pounds (net) when an NFPA 13 automatic sprinkler system is provided for the facility. This same tradeoff was discussed previously in relation to consumer fireworks storage. While it is clearly reasonable to exempt small amounts of commodity from more robust protection requirements, the exact limit and the dependence of this limit on sprinkler protection is still not well understood. Preliminary bench-scale experiments conducted by Battelle revealed that under certain conditions, as little as 5 cases of consumer fireworks (tanks, rockets, ground spinners, fountains and roman candles) produced an overwhelming fire scenario for a space equipped with a NFPA 13 wet pipe sprinkler system[47]. Although this is only 1 result, it underscores the need for a more scientific basis to support criteria for exempt amounts.

Also pertinent to this concept are exemptions for automatic sprinkler system protection on the basis of floor area of the space (Section 7.3.6). The basis for the limits of 6,000 ft^2 for new buildings and 7,500 ft^2 for existing buildings is unclear. For perspective on this issue, consider that these limits are not significantly below the floor area of the Ohio River Fireworks Store where the most relevant loss history for this commodity was established. Also, these criteria do not consider factors as significant as fuel loading within the space.

Criteria for fire alarms and means of egress are provided in reference to NFPA 101 with the special guidance in Section 7.2.3 that mercantile is the default occupancy group for the referenced evaluation. As referenced in Figure A3.3.74, the Life Safety Code provides addition sub-classification of the mercantile occupancy group in Classes A, B and C stores distinguished on the basis of height and area. This analogy is potentially incomplete in a fundamental way. As previously referenced in the analysis of analogous hazards in this report, the fundamental concept of the balance between allowable height and area with type of construction is based upon fuel loading. Fuel loading is implied by the intended use or occupancy of the space in question. For hydrocarbon-based fuels, the maximum severity of an enclosure fire is limited by ventilation into the space. As a result, there is an intended balance between size of the space, type of construction and fuel loading. This balance is disturbed when additional oxidizers are present within the enclosure. In the case of consumer fireworks, this may lead to maximum gas temperatures within the space that exceed ventilation-limited values. This is not to say that fire protection criteria for consumer fireworks retails sales facilities should not be similar to those of mercantile facilities; however, such specificity may be worthy of further evaluation in light of the previous discussion.

Means of egress requirements specific to egress travel distance and capacity of egress components are essentially based on a simplified evacuation model where flow to and through exits is simply a product of exiting speed and capacity. In reality, the exiting speed will be governed largely by awareness of the rate of hazard development. The speed of hazard development is a key issue with respect to consumer fireworks and existing research yields conflicting results. Experiments conducted by Wyle Laboratories[41], CHAF[44] and the State of Washington[45] all suggest a relatively slow developing hazard with ample time provided for egress for a light occupant load within a small facility. However, results of the Battelle[47] test series illustrated severe conditions occurring over a significantly more condensed timeframe. Such an occurrence could conceivably result in an overloading of exit capacity due to a corresponding increase in crowd speed. In other words, analysis of the speed of hazard development is essential to deriving appropriate means of egress requirements. To date, no experiments specific to egress from consumer fireworks retail sales facilities have been conducted. Furthermore, only 2 full-scale test efforts specific to retail sales facilities are known (Washington and Battelle). The conflicting nature of their results necessitates more focused research in this area.

Smoke and heat vents are required by Section 7.3.10 for consumer fireworks retail sales facilities or stores where the ceiling height is less than 10 feet and the travel distance to reach an exit is greater than 25 feet. Conceptually, this criterion is based on the idea of the total duration of egress occurring prior to deterioration of tenability within the space due to a descending smoke layer. However, smoke and heat venting was not a strategy employed in any of the known experimental efforts involving fire in consumer fireworks facilities. The only known experimental data with regard to smoke control for such facilities is in reference to the Battelle experiments in Ohio where forced ventilation was used and failed to achieve its objective of maintaining a clear tenable layer of air for egress purposes. Furthermore, given that the results of this particular testing program suggest the implementation of ESFR automatic sprinkler protection, the compatibility of smoke and heat vents with this technology must be questioned as the standard is developed.

A potentially promising method for achieving fire control is provided in the form of requirements for flame breaks in Section 7.3.15.3. Conceptually, flame breaks are designed to limit fire area. Toward this objective, they should be designed as noncombustible thermally robust barriers allowing minimal heat conduction to the unexposed side and extending beyond the shelving to limit potential convective and/or radiant heat exposure. Minimizing heat conduction may be accomplished by selecting a material either with the appropriate balance between thermal conductivity, thermal diffusivity and thickness. Requirements for flame breaks in the current standard are geared more toward slowing flame spread than halting it altogether. A total of 11 materials and associated thicknesses are specified in Section A.7.3.15.3 of the standard as being acceptable for use as flame breaks. It should be noted that materials such as 0.25 mm thick sheet aluminum would likely behave as thermally thin solids thereby offering little thermal protection to the unexposed side.

The approach of incorporating more mass into the overall storage arrangement is certainly effective in slowing the propagation of an accelerating reaction (i.e., high energy explosives); however, objectives for fire protection of consumer fireworks facilities are fundamentally different. If consumer fireworks retail sales facilities are to be treated as traditional mercantile occupancies with respect to NFPA 101 (which is thus far an incomplete analogy), fire protection objectives in these spaces must necessarily be consistent with either fire suppression or fire control as defined in NFPA 13. Fire control as defined in NFPA 13 is intended to correspond with confining flame spread to a design area (i.e., halting growth rather than simply slowing it). This may be accomplished with the use of thermally thick barriers within a shelving unit. It is important to recognize that thermally thin materials will not truly halt fire growth, but rather slow its spread over a relatively short time frame. Depending on the design, this time frame may not be sufficient to make an appreciable difference in prolonging tenable conditions within the space as currently asserted by the standard.

Consider also that the interior of the shelving unit will likely be partially shielded from automatic sprinkler protection at the ceiling level. Therefore, flame breaks will be exposed to a significant heat load, which may locally resemble an unsprinklered fire. For perspective, recall that the heat load produced by the 150 case full scale test conducted by Battelle[47] severely deformed the gondola shelving and even melted smoke detectors prior to sprinkler intervention. All things considered, selection and design of flame break materials should be a major focus of future research as certain methods potentially offer a very practical means for achieving fire control.

Tests conducted by Wyle Labs[41] and the State of Washington[45] reveal that the final packaging of consumer fireworks may play an important role in slowing fire growth beyond its incipient stage. In part, it is this observation that may lead to the hypothesis that thermally thin flame breaks will be particularly effective in slowing fire growth. However, there are a few important issues with respect to the global fire dynamics that must be considered. During the incipient stage, the total heat flux to exposed materials is quite low, thereby maximizing the insulating quality of relatively thin packaging. As illustrated in the Washington test, if the enclosure fire fails to grow beyond its incipient stage prior to utilizing the available ventilation within the space, the duration of the fire event will be significantly prolonged. In this case, the burning packaging requires ventilation to sustain combustion. As a result, with limited or no ventilation, the heat load generated by the smoldering packaging will remain low thereby minimizing the involvement of fireworks. However, for a case where fire progresses to a more robust stage of growth, as observed eventually in the Washington test and immediately in the Battelle tests[47], the insulating quality of thermally thin solids (i.e., packaging and thin flame breaks) becomes far less important.

To date, there is no known research focusing on designing flame breaks for maximum efficiency for fires in consumer fireworks retail sales applications. Nonetheless, very specific design criteria are provided in NFPA 1124. The scientific basis for these criteria, whether theoretical or experimental, should be referenced in the appendix of the standard.

Minimum separation distances for temporary consumer fireworks retail sales facilities include distances to nearby buildings, combustibles, other tents, vehicle parking, other stands and storage of consumer fireworks. Minimum distances range from 5-20 feet depending upon the application. The basis for this range of distances is unclear, particularly given the results of the Washington test which officially concluded a minimum separation distance on the order of 40 feet would be appropriate for many of the listed applications, despite projectiles traveling greater distances during the test[45]. Providing a discussion of the rationale behind specific separation distance requirements in the appendix of the standard may alleviate such apparent discrepancies between existing provisions and known experimental results.

Submitted by:

SCHIRMER ENGINEERING CORPORATION

Jonathan Perricone

Jonathan Perricone, P.E.
Associate Engineer

JP:jm:kh

S:\SNDGO\PROJECTS\JOB 2007\207069 Consumer Fireworks Retail and Storage (FPRF)\rpjp.257.Literature.Review.Final.
10.01.07.doc

REFERENCES

---

[1] Hoffer, P. Seven Fires: The Urban Infernos that Reshaped America. Public Affairs: New York, 2006.

[2] Quintiere, J. Fundamentals of Fire Phenomena. John Wiley & Sons, Ltd. : Chichester, 2006.

[3] Richardson, J. History of Fire Protection Engineering. National Fire Protection Association / Society of Fire Protection Engineers: Massachusetts, 2003.

[4] APA Standard 87-1, 2001 Edition.

[5] Hall, J. Jr. *Fireworks.* National Fire Protection Association, Fire Analysis & Research Division: June 2006.

[6] National Fire Protection Association, One-Stop Data Shop. *Fire Incident Data Organization*.

[7] Earls, A. “Safe ‘crackers”, NFPA Journal, May/June 2001. pp.95-96.

[8] Kyodo News International, “Fireworks explosion in Thailand kills 3, injures 83”, November 13, 2000.

[9] BBC News, “Guatemala Market Blaze Kills 15”, November 21, 2006.

[10] http://www.saunalahti.fi

[11] CNN.com, “Fireworks trigger explosions in Mexican town, killing 56”, September, 27, 1999.

[12] http://en.wikipedia.org/wiki/Mobile_home

[13] Milwaukee Journal Sentinel, “Man Charged in Fatal Store Fire was Refused Fireworks the Day Before”, July 5, 1996.

[14] www.interfire.org

[15] CNN – “Man Arrested in Fireworks Store Fire that Kills 8”, July 4, 1996

[16] Ramachandran, G, “Human Behavior in Fires – A Review of Research in the United Kingdom,” Fire Technology, 26, 2, pp. 149-155 (1990).

[17] Fruin, J. “Crowd Disasters - A Systems Evaluation of Causes and Countermeasures.” Inc. in U.S. National Bureau of Standards, pub. NBSIR 81-3261, July 1981 146 pp.

[18] http://www.popcurrent.com/tag/tultepec

[19] http://my.opera.com/dancingwithbulls/blog/

[20] Consultation with NFPA 1124 Technical Panel, photos courtesy of Elizabeth Buc.

[21] Zalosh, R. Industrial Fire Protection Engineering. John Wiley & Sons, Ltd, West Sussex, England: 2003.

[22] Best, R. “Storage Fire (*K Mart*) Falls Township, PA, June 21, 1982”, NFPA Fire Investigations: National Fire Protection Association, MA.

---

[23] Best, R. "$100 Million Fire in *K Mart* Distribution Center: Sprinkler Systems Overwhelmed". Fire Journal, March, 1983.

[24] Best, R. "Fire Walls that Failed: The *K Mart* Corporation Distribution Center Fire". Fire Journal, May 1983.

[25] Incroprera, F. and Dewitt, D. Fundamentals of Heat and Mass Transfer, fifth edition. John Wiley & Sons, New York, 2002.

[26] NFPA 430 *Code for the Storage of Liquid and Solid Oxidizers*, 2004 edition.

[27] Grant, C. "Halon Design Calculations." The SFPE Handbook of Fire Protection Engineering, 3rd edition. Society of Fire Protection Engineers, National Fire Protection Association, MA: 2002.

[28] Duval, R. "Storage Warehouse, Phoenix, Arizona, August 2, 2000", NFPA Fire Investigations: National Fire Protection Association, MA.

[29] Nugent, D., Oxidizing Pool Chemicals, NFPA Journal, 92, July/August 1998.

[30] Turns, S. An Introduction to Combustion: Concepts and Applications, 2nd edition. McGraw-Hill Companies, Inc.: Boston, 2000.

[31] Shidlovskiy, A. Principles of Pyrotechnics, 3rd edition. American Fireworks News: Washington, D.C., 1997.

[32] CHEMKIN™, Sandia National Laboratories

[33] Jin, T. "Visibility and Human Behavior in Fire Smoke." The SFPE Handbook of Fire Protection Engineering, 3rd edition. Society of Fire Protection Engineers, National Fire Protection Association, MA: 2002.

[34] Purser, D. "Toxicity Assessment of Combustion Products." The SFPE Handbook of Fire Protection Engineering, 3rd edition. Society of Fire Protection Engineers, National Fire Protection Association, MA: 2002.

[35] Conkling, J. "American Fireworks Manufacturing: An Industry in Transition". *Fire Journal*. National Fire Protection Association: Volume 80, No. 5, September 1986.

[36] Alenfelt, P. "Chemical Analysis of Consumer Fireworks". *Journal of Pyrotechnics*. Issue No. 11. Summer. 2000.

[37] Marlair, G., Turcotte, R., Kwok, Q., Branka, R. "Toxicity Issues Pertaining to Burning Pyrotechnics". Proceedings of the 9th International Symposium on Fireworks, Berlin, Germany: April 3-7, 2006.

[38] Wharton, R., and Chapman, D. "Use of the Term Sensitiveness to Describe the Response of Pyrotechnic Compositions to Accidental Stimuli". *Journal of Pyrotechnics*. Issue No. 7. Summer, 1998.

[39] Karlsson, B. and Quintiere, J. Enclosure Fire Dynamics. CRC Press: Washington, D.C., 2000.

[40] http://riodb.ibase.aist.go.jp/explosion/index_e.htm

[41] "Evaluation of the Hazards in Transportation from External Fires on Freight Containers Loaded with Common Fireworks." Wyle Laboratories Report No. 66810-1, Huntsville, Alabama, October 31, 1983.

---

[42] Myatt, S. “The Effects of External Fire on Fireworks Stored in Steel ISO Transport Containers”. *Journal of Pyrotechnics*, Issue 16, Winter 2002.

[43] Chapman, D. “Background and Introduction to the CHAF Project”, Proceedings of the 9th International Symposium on Fireworks, Berlin, Germany: April 3-7, 2006.

[44] Jakusz, B., Rados, M and Goryca, W. “Testing of Magazines Made from Steel and Special Concrete for Fireworks Storage of Hazard Division 1.4G and 1.3G”, Proceedings of the 9th International Symposium on Fireworks, Berlin, Germany: April 3-7, 2006.

[45] Lynam, D. “Fireworks Stand Test Burn.” *Fire Technology*, Vol. 37, Pages 153-166, Kluwer Academic Publishers: 2001.

[46] de Jong, E. and Ruiter, C. “Main Propagation Mechanisms of Fireworks”, Proceedings of the 9th International Symposium on Fireworks. Berlin, Germany: April 3-7, 2006.

[47] Fireworks Fire Suppression Systems Task Force: Report and Recommendation: January 31, 2000.

[48] NFPA 13 Standard for the Installation of Automatic Sprinkler Systems, 1999 Edition.

[49] Golly, L. “Final Test Report for Fire Suppression System Testing on 1.4G Fireworks Fires”, Battelle Edgewood Operations: January 11, 2000.

[50] Contestabile, E., R. Cameron, and M. Phillips, “Considerations for Establishing a Large Consumer Fireworks Distribution Centre (A case study)”, Proceedings of the 7th International Symposium on Fireworks. Valencia, Spain, 2003.

[51] McIntyre, F. “A Compilation of Hazard and Test Data for Pyrotechnic Compositions”, Contractor Report ARLCD-CR-80047: US Army Armament Research and Development Command: October 1980.

[52] *Recommendations on the Transport of Dangerous Goods, Model Regulations*, 14th rev. ed., United Nations.

[53] *Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria*, Fourth revised edition. United Nations: New York and Geneva, 2003.

[54] Conkling, J. “Regarding a Default System for Fireworks Classification”, 9th International Symposium on Fireworks. Berlin, Germany: April 3-7, 2006.

[55] Arpin, Jean-Luc. “The Authorization and Classification of Fireworks in Canada”, Proceedings of the 8th International Symposium on Fireworks”, Shiga, Japan: April 18-22, 2005.

[*] comment by author, not part of the options for the HSE

[56] Merrifield, R. “Hazards Associated with the Storage of Fireworks.” *Journal of Pyrotechnics*, Issue 14, Winter 2001.

[57] Hatanaka, S. “The Japan Pyrotechnics Association and Inspection of Consumer Fireworks”, 9th International Symposium on Fireworks. Berlin, Germany: April 3-7, 2006.

[58] 2006 International Building Code: Code and Commentary, Volume I. International Code Council, Inc, 2006. pp 3-12: 3-29.

[59] Bagley, M. “Control Systems for the Storage of Explosives, Including Fireworks”, *Journal of Pyrotechnics*, Issue 18, Winter 2003.