ANALYSIS OF A FLAMMABLE LIQUIDS FIRE LEADING TO A BACKDRAFT EXPLOSION

Robert Zalosh[1] and San-Ping Ho[2]
Firexplo
Wellesley, MA USA

ABSTRACT

A tragic backdraft explosion during a flammable liquids fire in the basement of a New York City hardware store caused three firefighter fatalities and numerous injuries on June 17, 2001. The backdraft explosion occurred soon after the firefighters forced open a locked door and boarded window. This paper presents a FDS code simulation of the fire leading up to the backdraft, and an analysis of the deflagration pressure produced by the backdraft. The gasoline pool and subsequent flammable liquid container fire heat release rate history was estimated using fire test data for flammable liquid container storage fires. The calculated oxygen and hydrocarbon gas concentrations at the time the basement door and window were opened satisfy recently reported backdraft occurrence criteria. Furthermore, the calculated temperatures at the upper elevations of the wall furthest from the suddenly opened window were sufficiently high to ignite the oxygen vitiated, hydrocarbon rich gas in the upper layer. Results suggest that the mixing layer was sufficiently thick to allow for rapid flame propagation through it after ignition at the wall on the opposite side of the basement. The large mixing layer and rapid flame propagation produced the deflagration pressures that occurred in this backdraft.

Introduction

Fleischman et. al. [1] define a backdraft as a rapid deflagration following the introduction of oxygen into a compartment filled with accumulated unburned fuel. Gottuk et al [2] describe the phenomena causing a backdraft by referring to the sequence of drawings shown in Figure 1. The first step in the development of a backdraft is the formation of a fuel-rich atmosphere in an oxygen-vitiated enclosure as represented by Diagram 1 in Figure 1. The second step is the sudden introduction of air into the enclosure by opening a door or window as illustrated in Diagram 2 of Figure 1. As the air flows into the enclosure under the hot fuel-rich gases flowing out, a mixing region develops at the boundary between the two streams as illustrated in Diagram 3. If the mixture becomes large before it encounters a sufficiently hot source to ignite it, then a deflagration occurs as illustrated in Diagrams 4 and 5. The expanding flame front generated in the deflagration pushes fuel-rich gases out through the enclosure opening followed by a fireball or flame jet. In the last diagram, a blast wave (shock wave propagating into the air outside the enclosure) propagates away from the enclosure at a speed somewhat greater than sound speed.

Most backdrafts start with the accumulation of smoke and pyrolysis products from incomplete combustion of solid fuels as the oxygen concentration starts decreasing in the enclosure. Croft's 1980 review [3] of 123 fires involving backdraft explosions with identified materials indicates that only 11 (9%) were due to volatile materials such as oil, paint, and alcohols. In the 1994 fatal backdraft at 62 Watts Street in Manhattan, Bukowski [4] reports that the fire started with the burning of a plastic trash bag on top of a lit gas stove in a particularly airtight renovated apartment building. Bukowski mentions that the fire also involved several bottles of liquor in the kitchen.

The objectives of this paper are 1) to describe the June 17, 2001 New York City flammable liquids tragic fire that culminated in a fatal backdraft explosion; 2) to present results of a FDS

[1] Professor Emeritus, Worcester Polytechnic Institute, USA
[2] Assistant Professor, Chang Jung Christian University, Taiwan, R.O.C.

simulation of the fire up to the time of the backdraft; and 3) to discuss the calculated species concentrations and temperatures in the light of the backdraft criteria developed in references 1 and 2.

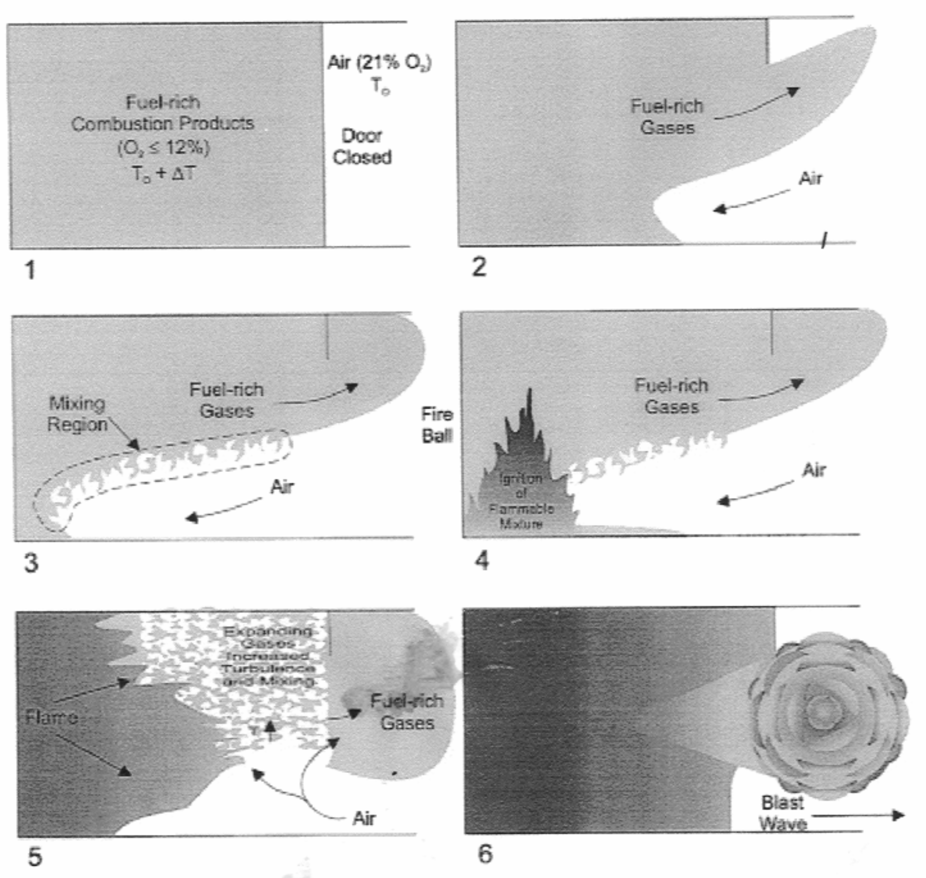

Figure 1 Backdraft development stages (from Gottuk et al, 2)

Building and Contents

The Long Island General Supply Co. property at 12-20 and 12-22 Astoria Boulevard in Queens, New York City was a typical neighborhood hardware store. Retail operations were conducted on the first floor. The basement was used for merchandise storage, shipping and receiving, paint blending, and equipment setup.

Figure 2 shows a plan view of the basement, which is actually composed of two buildings with a common wall. The 12-20 (West) side of the basement is a 20-ft wide by 55-ft (6.1m x 17m) long rectangle. The 12-22 (East) side of the basement is a trapezoid with widths of 51-ft and 8-ft (15.5m and 2.4m), and a length of 60-ft (18m). The 0.81m wide opening between the two sides of the basement was protected with a horizontal sliding fire door, but wooden dowels in the door floor-track and a plywood ramp over it prevented the door from closing. The basement height to the sheet rocked (gypsum board) ceiling is 1.9m. The entrance to the alley was on 14th St.

The 14th St. wall sloped down from Astoria Boulevard, and bore only a minor structural load. The two window openings on the 14th St. basement wall were covered with steel bars and sheet metal.

There was a double door at the rear of the basement that opened onto a ramp in the alley to facilitate merchandise delivery. The interior door was a heavy-duty iron door secured with two vertical bars about ¾” (19 mm) thick. There are also two horizontal steel bars across the door, which is intended to be opened from inside. The locked exterior wood door has sheet metal facing on both sides. A gas-fired hot water heater is situated at location A in Figure 2, with the center of the heater approximately 9 ft (2.7 m) in from the rear door. A gas-fired boiler is situated between the hot water heater and the rear door.

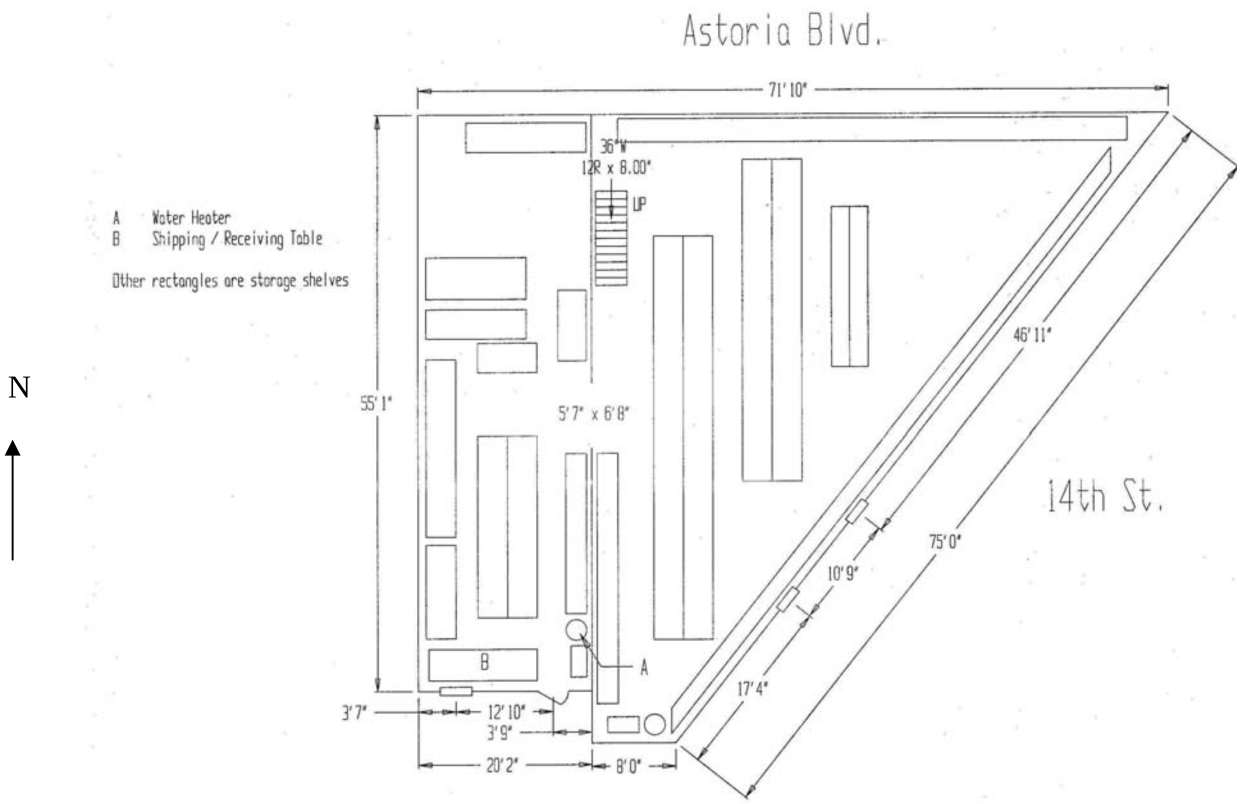

Figure 2. Basement layout and dimensions.

Flammable liquids stored in the basement are listed in Table 1. Stock along or near the rear wall included metal and plastic containers of paint thinner, lacquer thinner, naptha, paint remover (turpentine), floor refinisher (urethane), and various solvents including xylene, acetone, toluene, methyl ethyl ketone, and denatured alcohol (ethanol). Estimated total amounts of the various flammable liquids stored in both sides of the basement are listed in Table 1. The total volume of liquids listed is 233 to 252 gallons (862 to 932 liters), not including the numerous 1-gallon paint cans in the east (12-22) room.

Stock stored in the interior of the basement and along the wall dividing the two sides of the basement included numerous spray paint cans and 1-lb cylinders of propane and MAPP gas. One-gallon friction-lid cans of oil-based and water-based paint were stored primarily on the 12-22 (east) side of the basement. Various other hardware store items including cartons of plastic door chimes, light bulbs, plumbing supplies, and hand tools were distributed around the basement.

There were no fire/smoke detectors or suppression systems in the building. Residential apartments were situated on the second floor above the hardware store.

Table 1
Flammable Liquids and Gases in Basement

Flammable Liquid or Gas	Amount	Basement Locations
Acetone	6 – 12 Gallons	Rear of west side
Denatured Ethanol	24 Gallons	Rear of west side
Kerosene	4 Gallons	Rear of west side of basement
Lacquer Thinner	12 – 24 Gallons	Rear of west side
Methanol-Ethanol Blend	12 Gallons	Rear of west side
Methyl Ethyl Ketone	24 Gallons	Rear of west side
MAPP Gas	27 Cylinders	East side
Mineral Spirits	24 Gallons	Rear of west side
Naptha	24 Gallons	Rear of west side
Paint (mostly oil based) in 1-gal Cans	Unknown	East Side on shelves
Paint Thinner	24 Gallons	Rear of west side
Propane	142 14-oz cylinders	Most on east side; about 6 more near receiving area on west side.
Spray Paint (Oil based)	200 – 300 Cans	Rear of west side
Toluene	4 Gallons	Rear of west side
Turpentine	24 Gallons	Rear of west side
Xylene	4 Gallons	Rear of west side

Fire Incident

The fire started when a 13-year old boy accidentally knocked over an open or partially open plastic container of gasoline in the alley behind the store. The 1-gallon container apparently was not full of gasoline because New York Fire Department (NYFD) investigators later found rainwater in the container. The spilled gasoline flowed down the ramp leading to the rear basement door and puddled. A simulated spill (using water) by NYFD investigators indicated that the puddle would form 2 to 3 feet (0.6 to 0.9 m) inside from the rear door. Since the puddle is within a few feet from the water heater, presumably it did not take long for flammable vapors from the gasoline puddle to be ignited by the pilot flame in the water heater. There was a distinctive V-shaped fire damage pattern on the lower portion of the water heater, and on the stock situated near the water heater.

The first NYFD notification of the fire came at 2:21 PM from a telephone call. At approximately the same time, an eye witness hailed a NYFD fire engine company as they were returning from another run. The officer of the squad followed the eye witness to the alley and basement rear door of 12-20 Astoria Blvd. The officer heard fire crackling sounds behind the locked door.

Firefighters made several attempts to enter the hardware store through the locked front and rear doors. They eventually gained entry through the front door at 2:32 PM. They reached the interior first floor door to the basement a few minutes later, but were instructed to wait at the top of the stairs as entry was being attempted through the rear door.

As the firefighters waited at the top of the stairs, they would intermittently open the cellar door to observe conditions, and sometimes to discharge water from their hoseline nozzle. At first, they observed light grey smoke at the top of the doorway, and light blue flame at the bottom of the doorway. Later (2:37 PM), they observed flames filling the entire doorway.

Firefighters at the locked double rear door in the alley experienced great difficulty in forcing it open. At 2:42 PM, they managed to open the external door ajar about 18 inches, at which point it could not open beyond the metal bar inner door. An officer looked in through the partially open door, but did not see any flame. Another officer used the infrared imaging camera to see that there were high temperatures (reportedly 590 ^{o}C to 760 ^{o}C) at the basement ceiling.

During firefighting efforts, there were numerous verbal reports of a heavy smell of varnish. There were also numerous accounts of sounds of popping noises in the basement. The varnish smell was due to the vaporization of the many flammable liquids that were being released from breached containers. The popping noises were due to the ruptures of aerosol containers and closed flammable liquid containers as they were engulfed in the growing fire. Three propane cylinders also ruptured at some undetermined times during the fire.

While entry attempts were proceeding through the locked doors, other firefighters were attempting to open the two metal covered windows on the 14th Street wall of the basement. One window was opened at about 2:40 PM, and the second (north) window was opened at approximately 2:47 PM.

At 2:48 PM, a devastating explosion occurred. The 14th Street brick wall lifted up and out and crumbled on several firefighters. A firefighter on the first floor of the store was lifted up as the floor lifted and then fell into the basement, where he was beyond the reach of rescue efforts. Firefighters on the second floor were blown out the windows onto Astoria Boulevard. Firefighters at the rear basement door were lifted by the blast and thrown away from the building. Other firefighters on Astoria Boulevard were blown across the street. Detailed accounts of observations immediately prior to the explosion, and witness characterizations of the explosion are reported in the next section of this paper.

The two firefighters who were opening the covered windows on the 14th Street wall died from blunt trauma injuries caused by the wall being blown out. In addition to the three fatalities, approximately 50 firefighters and civilians suffered injuries of varying severity. The fire continued to burn for approximately one hour after the explosion when it was finally extinguished with foam suppressant.

Explosion Incident

Representative witness observations immediately prior to the explosion include 1) continued intense smell of varnish, 2) a change in the appearance of the smoke being vented from the building, and 3) rushing wind and sucking of air into the basement. The timing of these observations coincides with the forced opening of the 14th Street wall basement windows (particularly the north window) a few minutes after the rear basement door was pushed in to the inner metal bars.

Witnesses outside the building characterize the explosion itself as a thud, roar, or concussion. Firefighters inside the building do not really hear a noise but feel a wind that either lifts them up or blows them outside, depending on where they are located. Many witnesses describe dust and debris generated by the explosion. Some observers describe flame either around the perimeter of the building or emanating from the open doorways.

Many firefighters around the perimeter of the building were blown off their feet and landed 10 ft to 15 ft (3 to 4.6 m) away. Firefighters on 14th Street were struck by bricks (which landed as far as 30 ft from the wall) as the wall lifted up, blew out toward them, and came down in a rubble pile. There were numerous burn injuries as well as fall and crushing injuries.

Structural damage consisted of the blown out 14th Street wall and major damage to the front wall on Astoria Boulevard. After being bowed out at the bottom from the explosion, the front wall eventually came down also, and the roof partially collapsed.

It is difficult to determine with much accuracy the pressure needed to blow out the 14th Street un-reinforced brick wall. Since the shorter span basement rear wall did not blow, an approximate estimate is that the peak explosion pressure was probably in the range 0.3 psig to 0.6 psig (2 kPa to 4 kPa). There were no broken windows or any blast damage on the neighboring buildings.

FDS Simulation

Computational Fluid Dynamic (CFD) calculations of fire induced flows, temperatures, and oxygen concentrations were conducted with the Fire Dynamics Simulator (FDS) Version 2 computer code developed at the National Institute of Standards and Technology Building and Fire Research Laboratory. The theory and numerical method of solution used in FDS is described in the McGrattan et. al technical report [5].

The geometrical representation of the hardware store basement is shown in Figure 3. The grid cell size used was 0.1m by 0.1m by 0.1m. Besides the overall dimensions and layout of the 12-20 (West) side and 12-22 (East) side of the basement, the FDS input also included representations of shelf storage in both rooms. FDS "thermocouples" were placed at the locations designated as A, B, C, and D to obtain vertical profiles of gas temperatures and oxygen concentrations. Small ventilation openings were assumed as follows:

- Door gap (16-inch long by 1.0-inch high) under the rear door leading to the alley
- Small opening in ceiling above hot water heater in 12-20 basement
- Small openings (one cell wide) in South wall-ceiling intersection and West wall-ceiling intersection in 12-20 basement
- Small openings (one cell wide) in North (Astoria Blvd) wall-ceiling intersection and East (14^{th} St.) wall of 12-22 basement

A 3-ft by 8-ft (0.9 by 2.4 m) covering in the ceiling of the 12-22 basement at the top of the stairs was specified to open 15 minutes after fire initiation to represent the opening of the stairway door by responding firefighters. The doorway in 12-20 leading to the alley was specified to partially open 24-minutes after fire initiation such that the effective open area was 1.5-ft wide by 6.7-ft (0.46 by 2.0 m) high. One window in the 14^{th} St. wall was specified to partially open (2.5-ft by 1.5-ft) thirty minutes after fire initiation.

The fire heat release rate history was constructed from the following assumptions. The initial gasoline pool fire was assumed to be 0.56 m^2 in area, have a representative hydrocarbon specific burning rate of 55 g/m^2-s, a heat of combustion of 43.7 kJ/g, and a combustion efficiency of 0.92, such that the initial heat release rate is (55 g/m^2-s)(43.7 kJ/g)(0.56 m^2)(0.92) = 1238 kW = 1.2 MW. Assuming there was one gallon of gasoline spilled, the combination of burning rate and pool area implies that the gasoline would be consumed after 90 seconds of burning.

The gasoline pool fire ignited cartons of screws and cartons of plastic door chimes stored near the 12-20 basement rear door. It also ignited cartons containing plastic containers of paint thinner, which in turn allowed spilled paint thinner to augment the fire heat release rate. Eventually, spray paint cans were ruptured producing fireballs and pools of residual propellant and hydrocarbon spray paint. Later, these exposure fires caused the breaching of metal containers of hydrocarbon paint. Heat release histories for these storage commodities were estimated based on fire test data for similar commodities. The estimated times of ignition, heat release rate histories, and (in some cases) burn out times are listed in Table 2.

The total heat release rate is the sum of the contributions from the six commodities listed in Table 2. It is shown as a function of time in Figure 4. The actual heat release rate history used in the FDS simulations is the simpler curve shown in Figure 4 in which the heat release rate grows linearly from 1200 kW at t=0 to 3600 kW at 7 minutes after ignition, and remains at 3600 kW for the duration of the fire. The FDS fire is located in the southern half of the west (12-20) basement room.

Table 2
Estimated Heat Release Rate Contributions to Basement Fire

Commodity	Ignition Time from Start of Fire	Heat Release Rate History (kW)	Maximum Heat Release Rate (kW)	Burn-Out Time (sec)
Gasoline	0 sec	1200	1200	90
Cartons of Screws	10 sec	173	173	110
Plastic Chimes in Cartons*	20 sec	$0.21\times(t-10)^2$	1200	840
Paint Thinner in Plastic Container**	90 sec	$1200\times\left(\frac{t}{180}-90\right)$	2400	1500
Spray Pain Cans Pool Fire	95 sec	600	600	-
HC Paint in Metal Containers	300 sec	$22\times\left(1+\frac{99}{60}(t-300)\right)$	2200	-

*peak heat release rate 1200 kW from 100 to 540 sec; ** peak heat release rate 2400 kW at t = 450 sec

The calculated average oxygen concentrations in the west (12-20) and east (12-22) sides of the basement are shown in Figures 5 and 6, respectively. Results indicate that the 12-20 room-average oxygen volumetric concentration decreased from 21% to about 5% in the first 13 minutes of the fire, and remained between 5% and 7% until the time of the explosion. Oxygen concentrations in the hot gas layer under the ceiling were significantly less than 5% after the first 6 minutes of the fire. The 12-22 room-average oxygen concentration decreased to about 15%, and decreased further to about 9% at the time of the explosion. Details of both the oxygen concentration and temperature distributions are given in the 2002 report submitted to the NYFD [6].

The primary reason for the low oxygen concentration on the 12-22 side of the basement is the open fire door separating 12-22 from 12-20. The open door allowed air to flow into 12-20 under the hot combustion products that were flowing out of 12-20. When NIST used FDS to simulate steady-state fires with heat release rates of 500 to 2000 kW in the 12-20 side of the basement, they found that the fire door fusible link should have fused within 380 s of ignition and would have actuated door closer had it not been blocked open [7]. The NIST simulation of the resulting 2000 kW fire in an isolated 12-20 basement room indicated that the oxygen in 12-20 would have been consumed within 380 s.

Backdraft Analysis

Based on the results presented in references 1 and 2, there are three criteria for a backdraft to occur when a sudden opening is created in an otherwise enclosed room or building. First, the oxygen concentration in the enclosure at the time of the sudden opening and resulting air inflow has to be well below 12 mass percent. Second, the fuel vapor mass concentration in the enclosure must be greater than at least 10% [1], and possibly greater than 16% [2]. Third, there must be either a flame or a hot spot at a temperature well above the fuel vapor spontaneous ignition temperature in order to ignite the vapor-air mixture formed upon air inflow as indicated in Figure 1.

Oxygen concentrations presented in Figures 5 and 6 were well below 12 volume % at 1800 seconds after ignition in both basement rooms. Fuel vapor concentrations from the vaporizing flammable liquids and incomplete combustion were not explicitly calculated, but a rough estimate of the amount of liquid needed to reach a fuel vapor mass fraction of 0.15 in both rooms can be obtained from the room volumes. If we assume that at the point in the fire that the liquid is released, the oxygen concentration is too small to support combustion, and that the vent areas are so small that most of the vaporized liquid remains in the room, the results for a representative liquid, MEK, indicate that only 18 gallons (68 l) are needed in the west (12-20) basement room, and 36 gallons (136 l) are needed in the east (12-22) room. Since there were approximately 24 gallons of MEK alone stored on the 12-20 side of the basement, and another 200 gallons of other flammable liquids, there was more than enough liquid present at the time of the fire. Similarly, the hundreds of gallons of volatile hydrocarbon based paint on the 12-22 side of the basement are much more than the minimum required 36 gallons.

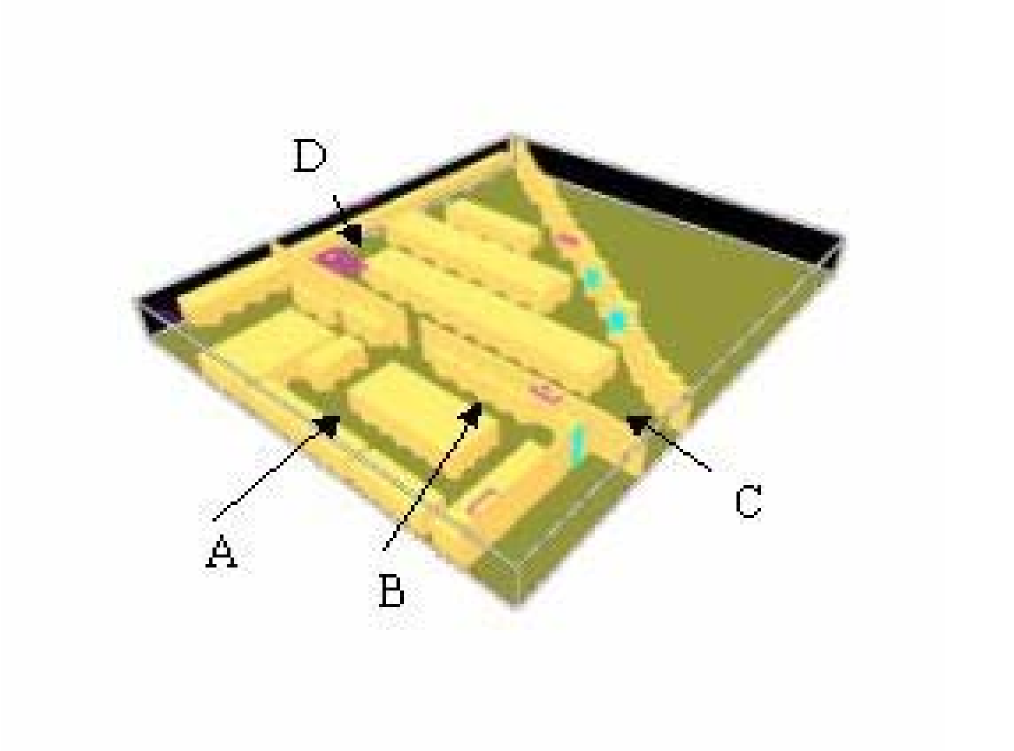

Figure 3 FDS representation of basement and contents.

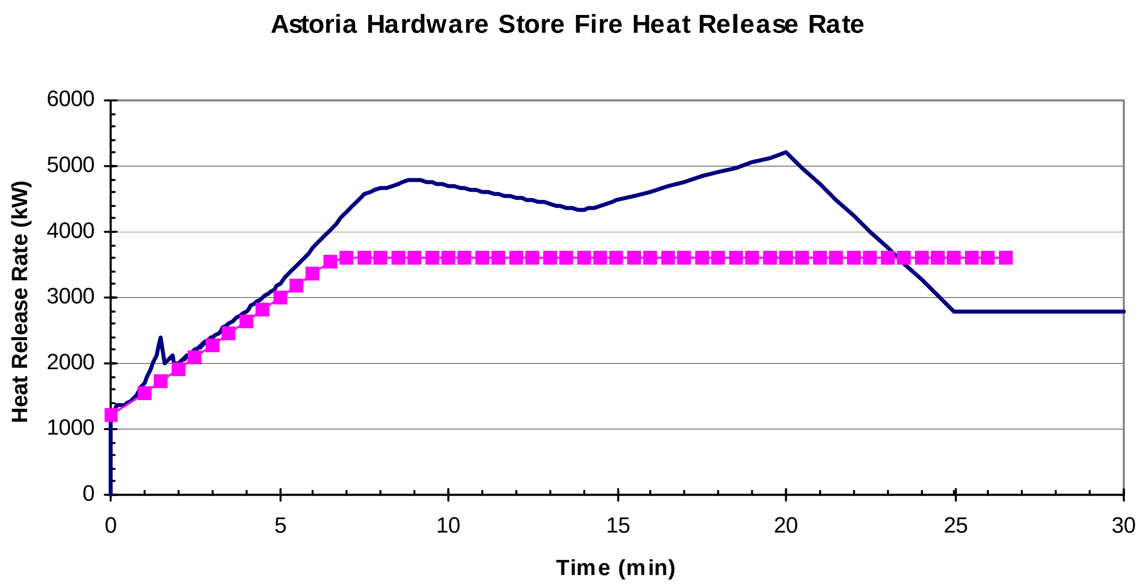

Figure 4 Heat release rate history used in FDS simulation.

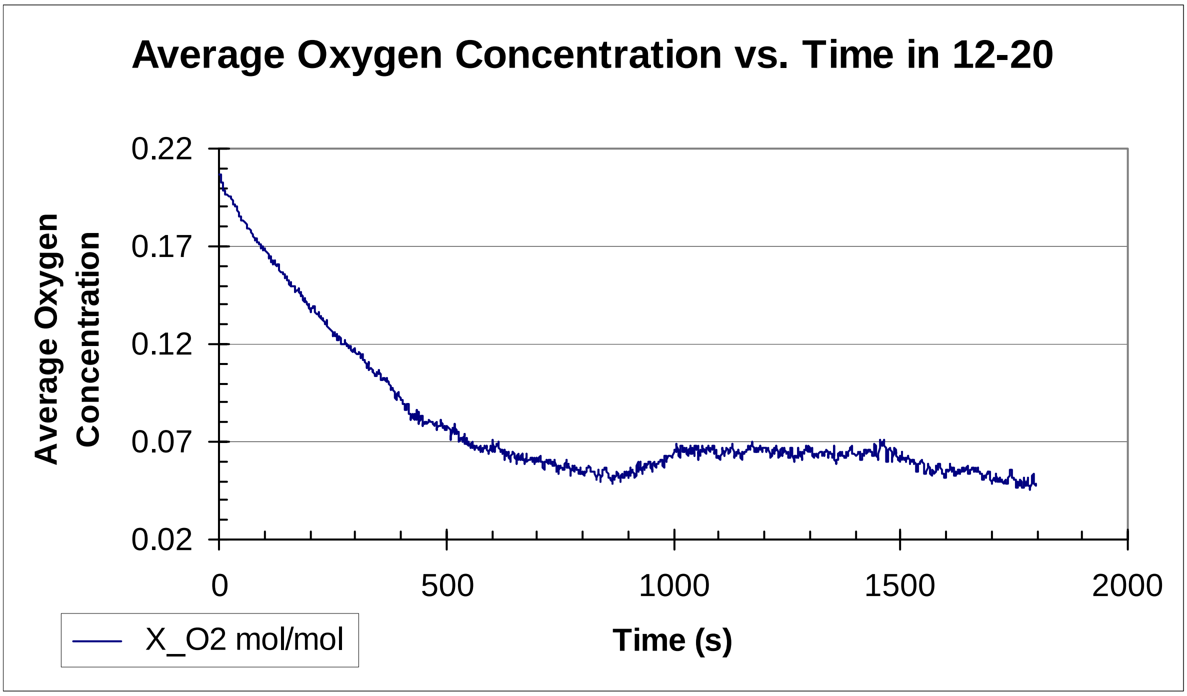

Figure 5. Average Oxygen Concentration versus Time in West Basement Room 12-20.

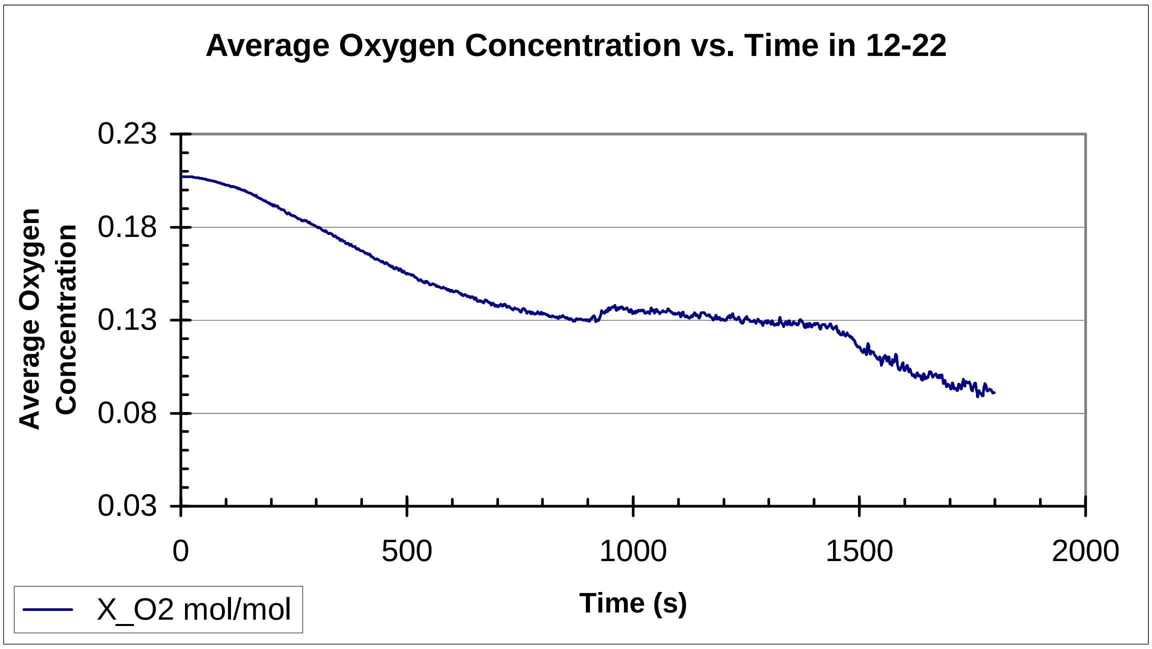

Figure 6. Average Oxygen Concentration versus Time in East Basement Room 12-22

FDS results indicated that ceiling gas temperatures in some parts of the 12-20 side of the basement rapidly reached about 500^{o}C, which is approximately equal to the auto-ignition temperature of propane and toluene, and about 100^{o}C above the auto-ignition temperature of MEK. Thus, all three conditions required for a backdraft were present in this fire: fuel vapor mass fraction greater than 0.15, average oxygen concentrations well below 12%, and local gas or wall temperatures above the auto-ignition temperature for the fuel vapor. Furthermore, the highest temperatures on the 12-22 (east) side of the basement were at the common wall between the two rooms, i.e. at a distance far from the suddenly opened windows on the 14th Street wall. This probably allowed a relatively large mixing layer to form before it encountered flame or temperatures that could ignite the mixing layer.

When a backdraft or any other gas-air deflagration occurs, the pressure generated depends to a great extent on the size of the fuel vapor-air mixing layer and the ratio of the open vent area to the total surface area of the room walls, ceiling, and floor. In order to prevent pressures from exceeding 0.5 psig (3.4 kPa) in a worse-case deflagration with most of the room filled with flammable mixture, the vent design ratios in NFPA 68-2002 require the entire 14th St. wall and the front wall of the basement to blow out. This explains why these walls did indeed blow out in this explosion, even though they were not intended to serve as deflagration vents. Furthermore, it also indicates why the pressure generated in this backdraft deflagration was much larger than the pressures measured during the backdraft testing described by Fleischman et al [1] and Gottuk et al [2]. Similarly vented gas velocities were sufficient to explain the observations described by witnesses [6].

Conclusions

FDS simulations of the fire that occurred in a New York City hardware store basement in June 2001 show that two of the three conditions needed for a backdraft explosion upon sudden air inflow were realized. Separate approximate estimates of the minimum fuel vapor concentrations needed for the backdraft explosion were also realized. The actual backdraft explosion in this incident apparently produced higher pressures and gas velocities than in most previous incidents and test programs because of the large volumes of the two basement rooms and the estimated pressure required to blow out the weakest external wall in the basement.

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