FIRE PATTERN REPEATABILITY: A LABORATORY STUDY ON GYPSUM WALLBOARD

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ABSTRACT

In 2009, the National Research Council (U.S) published a report identifying the research needs of the forensic science community. In the field of fire investigation, one of the specific needs identified was research on the natural variability of burn patterns. The National Institute of Standards and Technology (NIST) is conducting a multi-year study, with the support of the National Institute of Justice (NIJ) and the NIST Office of Law Enforcement Standards (OLES), to examine the repeatability of burn patterns. The primary objective of the study is assessing the repeatability of burn patterns on gypsum board exposed to a range of source fires. This paper will provide the results from the characterization of the source fires and the results of the pre-flashover fire pattern repeatability experiments.

Experiments were conducted with a natural gas fueled burner, a gasoline fueled pan fire, and polyurethane foam. The top surface of the burner or fuel was 0.30 m (1 ft) by 0.30 m (1 ft) with the top surface approximately 76 mm (3 in) above the floor. Replicate source fire experiments were conducted in an oxygen depletion calorimeter with each of the fuels, in order to examine the repeatability of the fires in terms of heat release rate. The flame movement and height for each fire was recorded with photographs and videos.

The fire pattern experiments were conducted in a three-sided structure with a full floor and partial ceiling constructed from wood framing and lined with painted gypsum board. The source fires were positioned against the rear wall, midway along its length. Replicate experiments were conducted with each fuel. A new piece of painted gypsum board was used for each experiment. The burn patterns were documented and analyzed for repeatability. The results are presented in terms of the fire pattern height, width, and total area.

INTRODUCTION

According to the United States Fire Administration, in 2006, the third highest cause of residential structure fires in the United States were intentional (incendiary or suspicious) fires. The leading cause of civilian deaths in residential structure fires were intentional fires, which accounted for 11.7 % of the fatalities. These intentional structure fires were also the leading cause of property loss, at more than 8% [1].

According to the National Fire Protection Association (NFPA), there are approximately 316,610 intentional fires set annually in the United States. The average civilian casualty rates during the period 2003 through 2006, were 437 civilian deaths and 1,404 civilian injuries. In 2006, 10 fire fighters died and 7,200 on duty fire fighters were injured at the scenes of intentionally set fires. More than $1.1 billion dollars (U.S.) was lost due to direct property damage. Only an estimated 28,000 intentional fires involved residential structures. Residential fires, however, accounted for more than 80% of the civilian deaths and injuries and more than 60% of the direct property damage from all intentional fires [2] .

The national clearance rate of arson fire cases is less than 20%, with a conviction rate of approximately 5% to 7%. Arson is a challenging crime to solve because typically there are no witnesses present at the time of the crime. According to the data that Flynn has analyzed, nearly two-thirds of intentional structure fires were either confined or limited to the object of origin [2].

Fires are investigated in order to determine the "origin and cause" of the fire and in some cases there is an effort to determine who was responsible for setting the fire. The fire investigation process must follow the scientific method as documented in NFPA 921, *Guide for Fire and Explosion Investigations* [3]. There are numerous textbooks on the subject of conducting a fire investigation [4-9]. The NFPA guide and the texts provide information to a fire investigator collecting data from the scene, analyzing the data, and developing a hypothesis about the fire.

Patterns produced by the fire are in many cases a significant portion of the data collected at the scene. One of the basic methods of documenting the fire scene is to photograph fire patterns. As noted by Icove and DeHaan, "the ability to document and interpret fire patterns accurately is essential to investigators reconstructing fire scenes…" [7]. A fire pattern is defined in NFPA 921 as, "the visible or measurable physical change, or identifiable shapes, formed by a fire effect or group of fire effects" [3]. Various types of fire patterns, such as; "V-shaped", "hour-glass", and "inverted cone", have come from common observation at actual fire scenes. As a result, the observations are typically qualitative in nature.

Previous fire pattern research by the National Institute of Justice (NIJ), the National Institute of Standards and Technology (NIST), and the United States Fire Administration (USFA) has shown that fire patterns provide data useful for the determination of fire origin. The reports noted the impact of ventilation on the development of the burn patterns [10-11]. A large number of other factors affect the formation of these patterns: burn time, heat release rate of the fire source, fire exposure, target fuel composition, adjacent fuel(s), compartmentation, and flashover to name a few. Given the limited number of experiments in the literature and the large number of variables involved, it has been difficult to fully understand a cause and effect relationship between the fire scenarios and the resulting patterns.

In 2009, the National Research Council of the National Academies (U.S) published a report identifying the research needs of the forensic science community. In the field of fire investigation, one of the specific needs identified was "…much more research is needed on the natural variability of burn patterns and damage characteristics and how they are affected by the presence of various accelerants" [12]. Previously, the Fire Protection Research Foundation convened a Research Advisory Council on Post-fire Analysis in 2002. Recommendations for research and developments in their white paper included; "advance the capabilities of computational fluid dynamics fire modeling, particularly as applied to fire ignition scenarios and fire pattern development and interpretation" [13].

A multi-year study to examine the repeatability of burn patterns has been started. In order to examine the repeatability of the burn patterns, the repeatability of the initial fires that cause the damage must be well characterized. This paper will focus on the initial results of the pre-flashover fire pattern repeatability experiments.

TECHNICAL APPROACH

A series of experiments was conducted to characterize a range of representative pre-flashover fires that can be expected from intentional and accidental fires. A fixed fire source footprint, 0.30 m (1 ft) square was chosen for this study and a range of common fuels were selected. The fires were positioned under an oxygen consumption calorimetry hood to determine the heat release rate. Heat release rate and total heat flux from the flames were measured and flame movement and height were recorded with photographs and videos. Given the focus on residential fires, small source fires were selected so that the burn pattern would be limited to less than 2.4 m (8 ft) in height. Replicate experiments were conducted with each of the fuels, in order to examine the repeatability of the fires and to quantify the variability in the flames.

Fuels

Several different fuels were used in this study. Experiments were conducted with a natural gas fueled burner, a liquid fueled pan fire, and a solid fuel. Natural gas was chosen as a fuel because it is used for calibrating the oxygen depletion calorimeters in NIST's Large Fire Laboratory. Therefore the heat content of the gas was monitored and mass flow controlled to provide a heat release rate based on fuel flow for comparison with the heat release rate values measured with the calorimeter. The gas burner arrangement provides the most idealized fire, in that it can be ignited and brought up to a near steady state heat release rate within a few seconds and then be shut down just as quickly. This is important in future phases of the study for determining the amount of energy transferred to the exposed surface.

Gasoline was the fuel of choice for the liquid fueled pan fire. Gasoline is not an ideal fuel to use in experiments due to the many components and additives that are specific to manufacturers, change from season to season, and vary based on requirements or restrictions of the locality. Gasoline is a real fuel and fire incident data shows that gasoline was the first item ignited in the majority of intentional fires where flammable or combustible liquids were used [14]. In addition, data from forensic laboratories, collected by Babrauskas and others, indicates that gasoline is the most prevalent accelerant found as part of the analysis of fire debris samples [15, 16].

Polyurethane foam was chosen as the solid fuel. According to the Polyurethane Foam Association, flexible polyurethane foam is the most widely used cushioning material in upholstered furnishing and mattresses. More than 1.7 billion pounds are produced in the U.S. every year [17,18]. In Rohr's study, "Products First Ignited in U.S. Home Fires", upholstered furniture and mattresses and bedding were the first items ignited in 33% of the fatal fires in the U.S. based on averaged data from 1999 through 2002 [19].

Fire Source Characterization

The fire source heat release rate experiments were conducted in the NIST Large Fire Research Laboratory's 3 m by 3 m oxygen depletion calorimeter. The expanded uncertainty of this device has been estimated as ±11% on the measured heat release rate. Details on the operation and uncertainty in measurements associated with the oxygen depletion calorimeter were documented by Bryant et.al. [20]. The data was recorded at intervals of 1 s on a computer based data acquisition system. The fires were centered under the hood of the calorimeter on a non-combustible platform measuring 0.91 m (3.0 ft) x 1.2 m (4.0 ft) x 12 mm (0.5 in) thick.

The natural gas burner was 0.30 m (1 ft) on a side and the top surface of the burner was 76 mm (3 in) above the floor. The shell of the burner was made from steel and filled with “pea sized” gravel with an average diameter of 6 mm (0.25 in). A steady state heat release rate of approximately 80 kW was used for the experiments.

The gasoline pan fire used 500 mL of unleaded, 87 octane gasoline. The pan was constructed from 6 mm (0.25 in) thick steel. The inner dimension of the pan was 0.305 m (1 ft) on a side and 19 mm (0.75 in) high. The pan was elevated in order to bring the pan lip height up to 76 mm (3 in) above the floor. The 500 mL of gasoline gave a fuel depth of 5.5 mm (~0.25 in) and provided a burn time of approximately 5 minutes.

The solid fuel was composed of polyurethane foam, with a density of approximately 23 kg/m^3. Each block of foam was 0.30 m (1 ft) on a side and was 76 mm (3 in) thick. The bottom and sides of the foam block were wrapped in aluminum foil to prevent the fuel from moving or spreading as it burned. Replicate experiments were conducted with each of the fuels.

Flame Heights

Each of the experiments was photographed with a digital SLR camera, fixed on a tripod, with a capability of capturing at least 5 images per second. Located adjacent to the camera was a video camera recording images at approximately 30 frames per second. In this paper, the mean flame height for each fuel was determined from the still photographic images. Examples of the types of images are presented in Figures 1 and 2. Figure 1 presents a photograph of the natural gas flame taken during a period of “steady state” burning at approximately 80 kW and a photograph of the polyurethane foam taken near its peak heat release rate of approximately 60 kW. Figure 2 presents two photographs of the same gasoline fueled fire when it was burning near its peak heat release rate of 100 kW. The two photographs, taken 0.2 s apart, represent the range of the observed flame heights from one of the gasoline experiments from 0.65 m (2.1 ft) and 1.0 m (3.3 ft), respectively. Table 1 provides the mean visible flame height, as well as the range of flame heights for each fuel, based on analysis of the photographs. In each case, the photographs were chosen for analysis while the fire was generating its peak heat release rate.

Table 1. Mean visible flame height and averaged minimums and maximums (Range) of visible flame heights for each of the fuels during peak heat release rate.

Fuel	Mean H_f Photographs (m)	Range H_f Photographs (m)
Natural Gas	0.70	0.50 to 0.98
Gasoline	0.84	0.52 to 1.1
Polyurethane Foam	0.46	0.30 to 0.78

Figure 1a and 1b. Photographs showing a natural gas flame (left) and a polyurethane foam fueled experiment (right) under the oxygen depletion calorimeter.

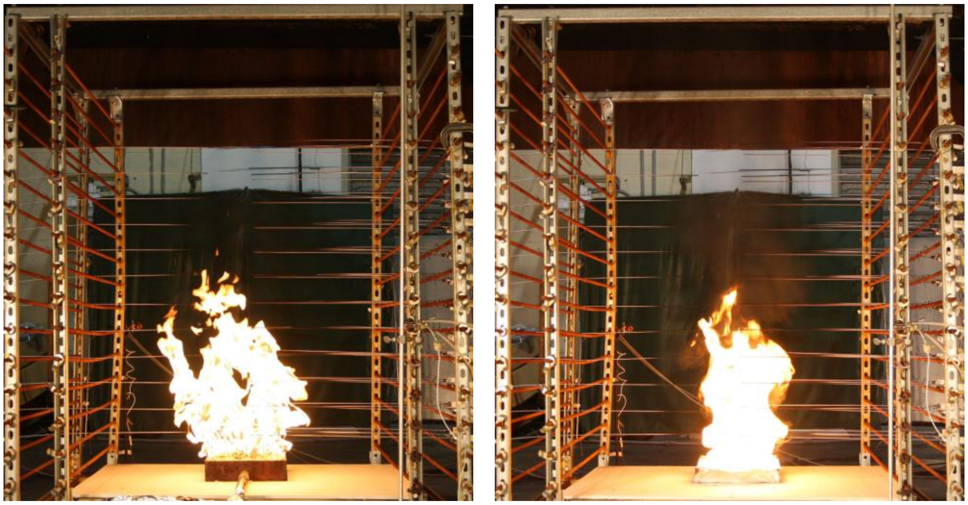
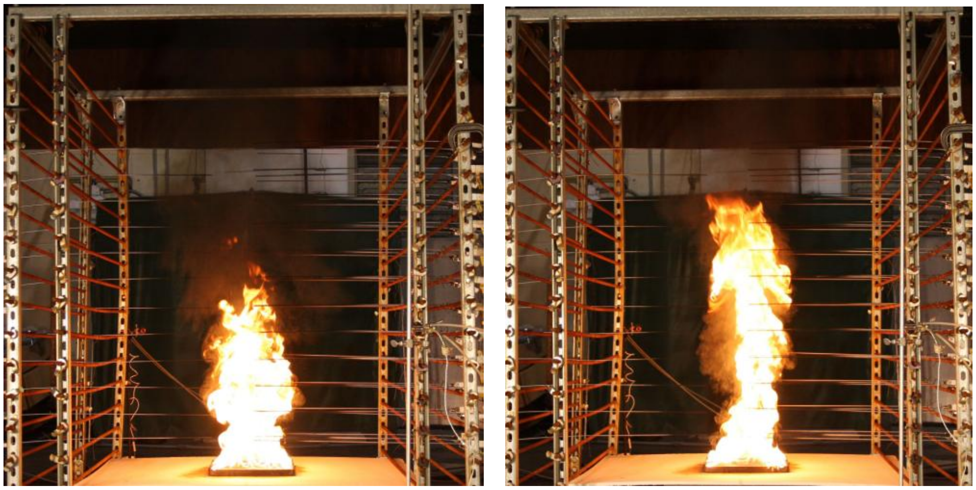


Figure 2a and 2b. Photograph showing a gasoline fueled experiment with a flame height of 0.65 m (left) and a photograph taken approximately 0.2 seconds later with a flame height of 1.0 m (right).



Heat Release Rate

Figures 3 through 5 are graphs showing heat release rate versus time for the natural gas, gasoline and polyurethane foam fueled fires. Each experiment has a unique label and symbol. In each graph, the replicate heat release time histories are overlaid to give a sense of the repeatability for each fuel. The results support the premise of why these fuels were chosen. The natural gas burner provided the most repeatable results, with an average steady state heat release rate of approximately 80 kW with an average total heat release of 23.3 MJ over the 300 second period after ignition. The gasoline, based on an average of the 18 experiments, had a peak heat release rate of approximately 80 kW sustained from 50 seconds to 100 seconds after ignition, yielding 13.6 MJ of total heat release over 300 second period after ignition. The polyurethane foam demonstrated the largest variability, as shown in Figure 5, of the three fuels in terms of peak heat release rate and time to peak heat release. Averaging the ten experiments yielded an average peak heat release rate of approximately 45 kW at 105 s, with a total heat release of 4.3 MJ over a 260 second period after ignition.

Figure 3. Heat release rates versus time for natural gas burner experiments.

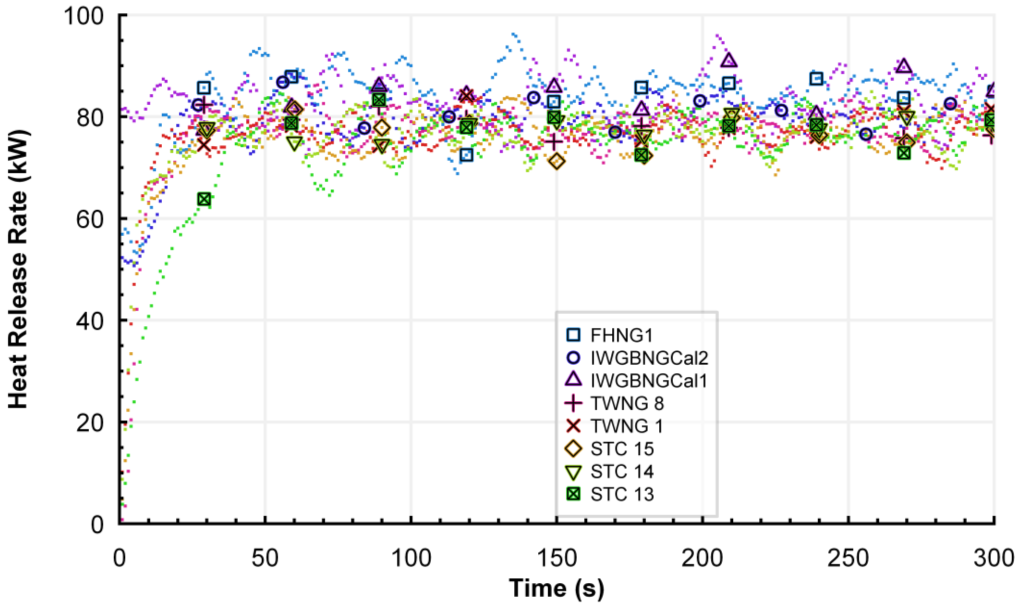


Figure 4. Heat release rates versus time for gasoline fueled experiments.

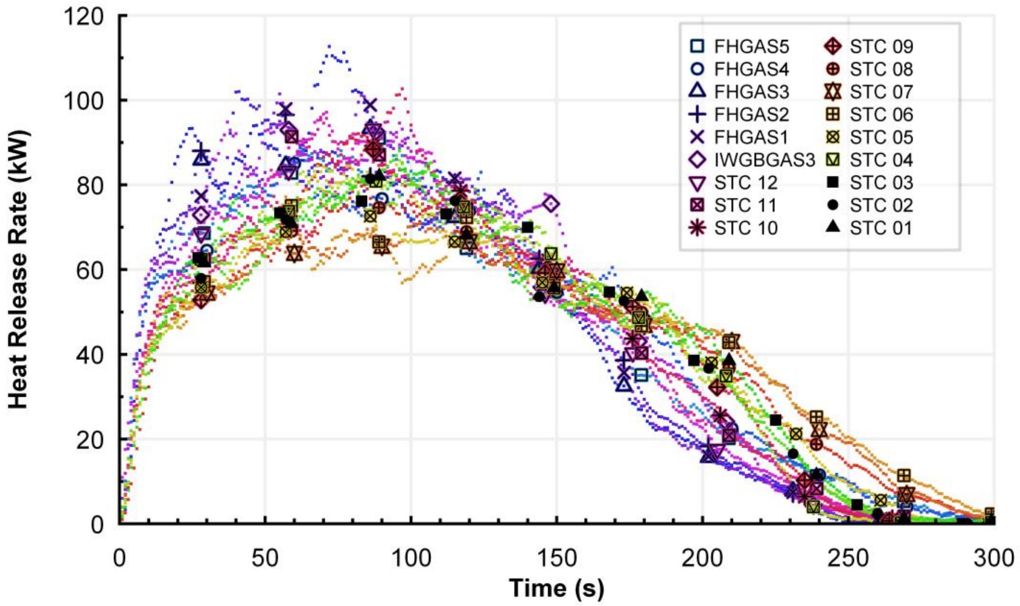
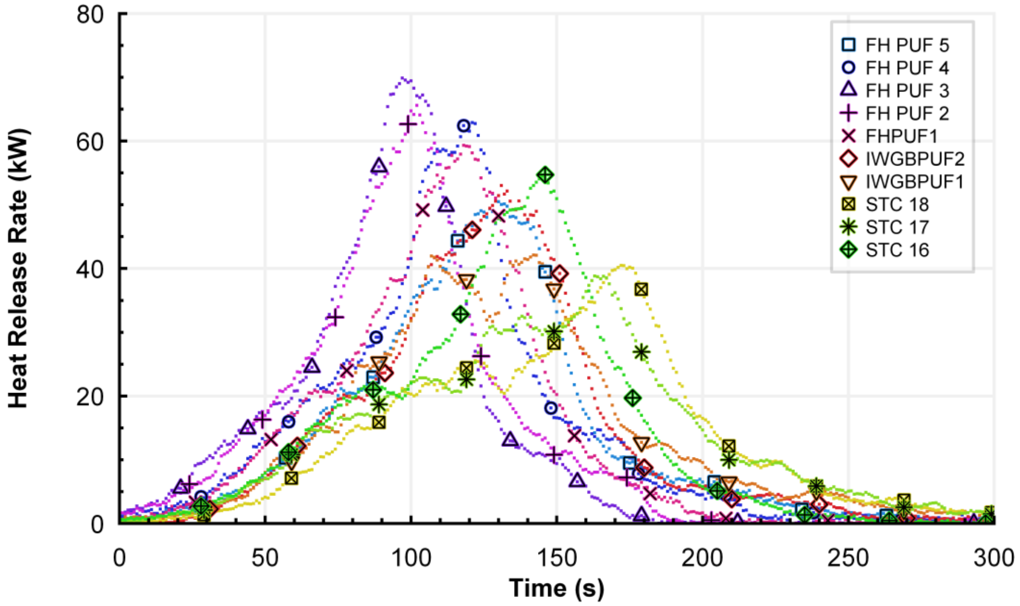


Figure 5. Heat release rates for polyurethane foam fueled experiments.



FIRE PATTERN EXPERIMENTS

Each of the test compartments consisted of three 3.6 m (12 ft) long by 2.4 m (8 ft) high wood framed walls. The wood elements of the frame were composed of kiln dried fir with a nominal cross section of 90 mm (3.5 in) by 38 mm (1.5 in). The interior surface of the walls was composed of 12.7 mm (0.5 in) thick, regular core gypsum wallboard. A partial ceiling with a width of at least 1.2 m (4 ft), measured from the back wall of the compartment was installed across the width of the compartment. The back wall of the compartment consisted of three gypsum board panels, each 1.2 m (4 ft) wide and 2.4 m (8 ft) high. For the experiments discussed here, the center panel was exposed to the source fire. Each panel was painted with a primer coat and a cover coat of latex paint. At least 9 experiments were conducted with each fuel, centered on the middle panel of the back wall. The top of the fuel/burner in each case was positioned 76 mm above the floor of the compartment. Each of the painted gypsum board panels that was used for a fire pattern, had a 50 mm (2 in) grid drawn on it to assist with the determination of the geometry of the fire pattern.

Each fuel or burner was positioned against the face of the painted gypsum board and ignited. The natural gas had a 300 second burn time which was approximately the upper bound for the total burn time for the gasoline and the polyurethane foam. The gasoline and polyurethane foam fires were allowed to burn until all of the fuel was consumed and the fires self extinguished. Once the fire was out, the pattern was photographed for future analysis. Then the pattern was measured. The grids were used to assist with the determination of the area. In order to measure the dimensions of the fire pattern a determination had to be made as to where the fire pattern stops.

Figure 6. Fire pattern compartment located under 10 m hood in the NIST Large Fire Laboratory. In this case a corner fire pattern was being generated.

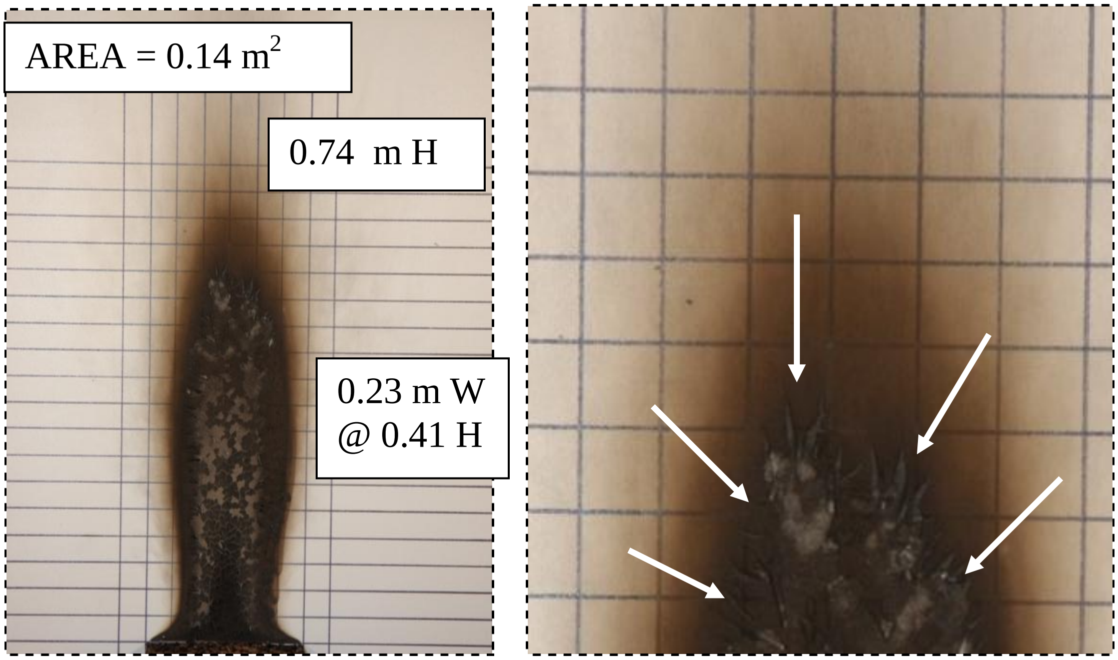
DeHaan[6] categorizes the fire effects that form patterns as follows:

1. Surface deposits
2. Surface thermal effects
3. Charring
4. Penetration
5. Consumption

For this analysis, the outline of the fire pattern was defined where penetration and consumption of the paper covering the gypsum wallboard stopped. Figure 7a and 7b show a near ideal fire from a natural gas fire. However, even in this case there are gradients to the amount of char. Hence the most definitive line of demarcation was the line where the paper covering over the gypsum board core was either burned completely away exposing the gypsum (consumed) or burned and lifted with portions still attached to the gypsum (penetrated). This was the line of demarcation chosen for this analysis.

Figure 8 shows three different fire patterns that were caused by exposure to the gasoline fire source. The photographs in this figure provide a sense of the level of pattern repeatability under well controlled conditions. Table 2 provides the average maximum height, average maximum width, average height at which the maximum width occurred and an estimate of the averaged area. The number of experiments included in each average is shown in column 1. Each dimensional value is presented with the 95% confidence level (2σ) based on Type A statistical analysis of the fire pattern measurements.

Figures 7a and 7b. A photograph (left) of a typical fire pattern from the natural gas fuel exposure with typical measurements and photograph of the top potion of the same pattern with portions of the line of demarcation used for the analysis highlighted with arrows.



Figures 8. Photographs from 3 different fire patterns generated with the gasoline fire.

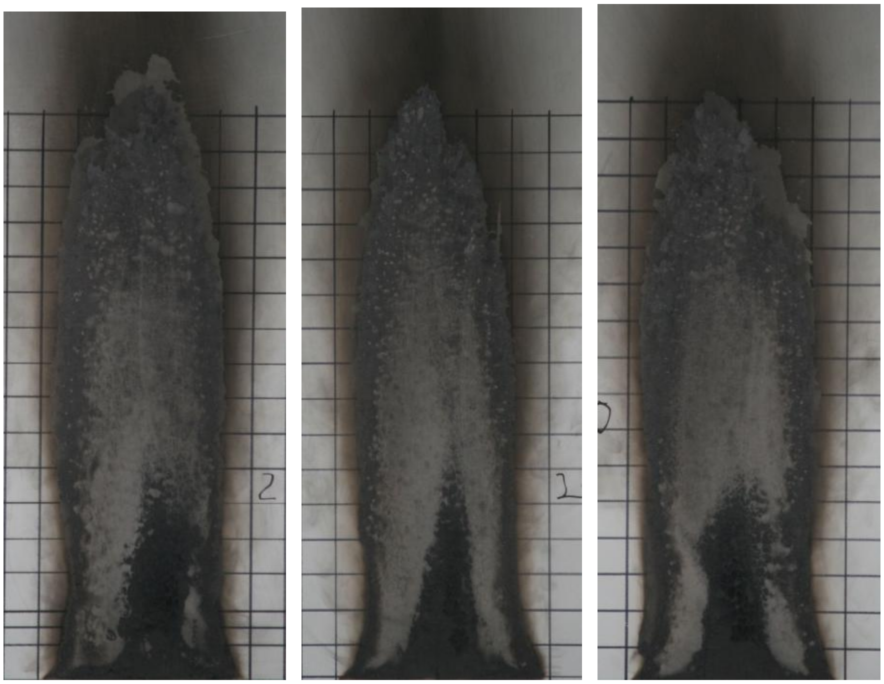


Table 2. Fuel Comparison Fire Pattern Dimensions with 95% Confidence Limits

Fuel (number of experiments)	**Height (m)**	**Width (m)**	**Height @ Max Width (m)**	**Area (m^2)**
Natural Gas (10)	0.74 ± 16%	0.24 ± 25%	0.41 ± 17%	0.15 ± 33%
Gasoline (12)	0.83 ± 18%	0.28 ± 32%	0.44 ± 41%	0.17 ± 25%
Polyurethane Foam (10)	0.24 ± 50%	0.28 ± 29%	0.04 ± 60%	0.05 ± 57%

The patterns generated by the polyurethane foam fueled fires have a higher variability relative to the natural gas and gasoline generated patterns. The polyurethane foam exhibited a higher variability of fire growth, a lower peak heat release rate, and a lower total heat release, than the other two fuels, which appears to have led to the pattern variability. The height of the natural gas and gasoline generated fire patterns are similar to the mean flame heights for the respective fuels.

Impact of Wall Construction

Additional experiments were conducted with the natural gas and gasoline fires to examine the impact of the method of construction of the walls on the development of the fire patterns. Three cases were examined: 1) Open back, 12.7 mm thick, regular core, painted gypsum board on the front of a wood frame only, 2) Closed back, 12.7mm thick, regular core, painted gypsum board on the front and back of a wood frame representative of an interior wall, and 3) Insulated,12.7 mm thick, regular core, painted gypsum board on the front and back of a wood frame, with fiberglas batt insulation in the voids of the wood frame representative of an exterior wall.

Figure 9. Photographs of fire patterns generated with the natural gas fire. Examples of experimental results for each of the three different wall construction types are shown.

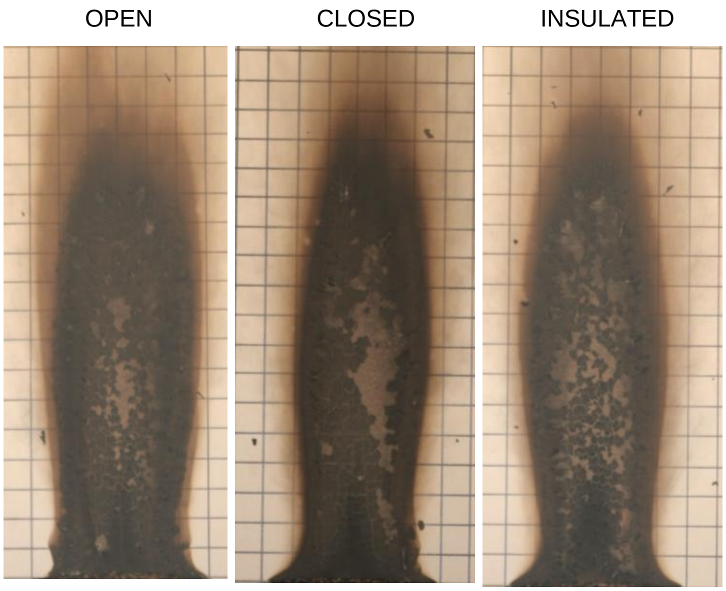

OPEN CLOSED INSULATED

Table 3 provides a comparison of the average maximum height, average maximum width, average height at which the maximum width occurred and an estimate of the average area for each of the three wall construction types. Ten experiments were conducted for each fuel and wall type with the exception of gasoline with the open back wall construction, which had 12 experiments. Each dimensional value is presented with the 95% confidence level (2σ) based on Type A statistical analysis of the fire pattern measurements.

Table 3. Comparison of Fire Pattern as a Function of Wall Construction Type. Values presented with 95% confidence limits.

Fuel (number of tests)	**Wall Type**	**Max Height (m)**	**Max Width (m)**	**Height @Max Width (m)**	**Area (m^2)**
Natural Gas (10)	Open	0.74 ± 16%	0.24 ± 25%	0.41 ± 17%	0.15 ± 33%
Natural Gas (10)	Closed	0.74 ± 8%	0.24 ± 7%	0.43 ± 7%	0.14 ± 6 %
Natural Gas (10)	Insulated	0.71 ± 14%	0.23 ± 17%	0.42 ± 17%	0.15 ± 14%
Gasoline (12)	Open	0.83 ± 18%	0.28 ± 32%	0.44 ± 32%	0.17 ± 24%
Gasoline (10)	Closed	0.80 ± 13%	0.29 ± 14%	0.44 ± 14%	0.17 ± 24%
Gasoline (10)	Insulated	0.82 ± 11%	0.25 ± 32%	0.40 ± 32%	0.13 ± 30%

SUMMARY

A series of experiments were conducted to examine the repeatability of pre-flashover fire patterns generated from exposure to short duration (300 seconds max.) well characterized fires. Three different fuels were used; natural gas, gasoline, and polyurethane foam. Each fuel had a similar top surface area. The heat release rate data showed that variability in the flame is greater for more complex fuels. In other words, the variation in peak heat release rate with the natural gas was similar to the expanded uncertainty of the measurement system ±11%, while the variation in the peak heat release rates of the gasoline and the polyurethane foam increased due to increased uncertainties in the fuels. The patterns generated by the polyurethane foam fire, had more variability than the natural gas and the gasoline fire patterns. This is due to the greater variability of the burning of the solid fuel and the lower heat release rate. The maximum fire pattern heights generated from the natural gas and gasoline fires were shown to have uncertainties of ±18% or less based on a Type A statistical analysis with 95% confidence limits. The 95% confidence limits of the other measurements were ±33% or less. Given the short durations of the fire, the different wall constructions had no significant impact on the fire patterns.

FUTURE RESEARCH

Efforts are underway to use digital image analysis to generate improved estimates of flame height from the source fires and the fire pattern areas. One of the challenges is the line of demarcation that is distinct and has a high level of contrast with the “unburned” section of the target fuel. The final step in this research program will be to use the NIST Fire Dynamics Simulator (FDS) and Smokeview programs to examine the ability to reproduce the source fires and the resulting damage patterns to the gypsum wallboard.

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REFERENCES

1. Causes of Residential Fires: 2006 Partial NFIRS Data, http://www.usfa.dhs.gov/downloads/xls/2006_Causes100506.xls. U.S. Fire Administration, Emittsburg, MD., Downloaded 10/21/08.
2. Flynn, Jennifer, D., *Intentional Fires.* National Fire Protection Association, Quincy, MA., May 2009.
3. NFPA 921, Guide for Fire and Explosion Investigations, NFPA, Quincy, MA, 2008 Edition.
4. Almirall, José R. and Furton, Kenneth G., Editors, Analysis and Interpretation of Fire Scene Evidence, CRC Press, Boca Raton, 2004
5. Daeid, Niamh Nic, Editor, Fire Investigation, Boca Raton, CRC Press, 2004
6. DeHaan, John D., Kirk's Fire Investigation, Sixth Edition, Pearson Prentice Hall, Upper Saddle River, NJ., 2007.
7. Icove, David J., and DeHaan, John D., Forensic Fire Scene Reconstruction, Second Edition, Pearson Prentice Hall, Upper Saddle River, NJ., 2009.
8. Lentini, John J., Scientific Protocols for Fire Investigation, CRC Press, Taylor & Francis Group, Boca Raton, FL., 2006.
9. Noon, Randall, Engineering Analysis of Fires and Explosions, CRC Press, Boca Raton, FL., 1995.
10. Shanley, James H., "USFA Study of Fire Patterns." U.S. Fire Administration, Emittsburg, MD., 1998.
11. Putorti, A.D., "Full Scale Room Burn Pattern Study." National Institute of Justice, Washington D.C., NIJ Report 601-97, December 1997.
12. Strengthening Forensic Science in the United States, A Path Forward. National Research Council of the National Academies. The National Academies Press, Washington D.C., 2009.
13. Fire Protection Research Foundation, Recommendations of The Research Advisory Council on Post-fire Analysis, Quincy MA, February 2002.
14. Rohr, Kimberly, D., "The U.S. Home Product Report, Forms and Types of Materials First Ignited in Fires: Flammable or Combustible Liquids." National Fire Protection Association, Quincy, MA., December 2001.
15. Babrauskas, Vytenis, Ignition Handbook. Fire Science Publishers, Issaquah, WA 2003. page 683.
16. Chasteen, Carl. Division of the State Fire Marshal, State of Florida, personal communication, April 2010.
17. Flexible Polyurethane Foam: Industry at a Glance. Polyurethane Foam Assn, Inc Knoxville, TN., 2007.
18. In Touch, Information on Flexible Polyurethane Foam. Polyurethane Foam Assn, Inc. Wayne, NJ., Vol. 2, No. 3., 1992.
19. Rohr, Kimberly D., Products First Ignited in U.S. Home Fires. National Fire Protection Association, Quincy, MA, April 2005.
20. Bryant, R.A., Ohlemiller, T.J., Johnsson, E.L., Hamins, A.H., Grove, B.S., Guthrie, W.F., Maranghides, A., and Mulholland, G.W., *The NIST 3 MW Quantitative Heat Release Rate Facility: Description and Procedures*, National Institute of Standards and Technology, Gaithersburg, MD, NISTIR 7052, September 2004.