

# **FIRE PATTERN PERSISTENCE AND PREDICTABILITY ON INTERIOR FINISH AND CONSTRUCTION MATERIALS DURING PRE AND POST FLASHOVER COMPARTMENT FIRES**

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## **EXTENDED ABSTRACT**

Fire Patterns, as defined by NFPA-921 are the visible or measurable physical effects that remain after a fire. Fire Pattern analysis has been a key factor in the determination of the origin and cause of fires for the past 50 years. In 1985 the Advanced Fire Patterns Project was formed between the National Association of Fire Investigators (NAFI) and the Fire and Safety Engineering Technology Program, Eastern Kentucky University to complete research into the development of fire patterns on exposed surfaces. Since the formation of the project, considerable work has been undertaken to study fire growth and spread in both full scale and ¼ scale test burns. Much of the data generated has been utilized to supplement instruction in the area of Fire Pattern Analysis.

To date, more than seventy full-scale, half-scale, and quarter-scale burn tests have been completed at EKU as a result of the seminars sponsored by NAFI, EKU and later also co-sponsored by the National Fire Protection Association (NFPA). The research burns have enhanced the knowledge base of the fire investigation community.

Separate from the work done by the AFPRP, the National Institute of Standards and Technology, Center for Fire Research obtained funding from the United States Fire Administration to conduct full scale fire tests to study Burn Patterns. This research began in November 1994 with the final report "USFA Fire Burn Pattern Tests"<sup>6</sup> issued in 1997. Included in the summary of results is the confirmation that "many of the concepts, investigative systems, dynamics of pattern production, and patterns analysis concepts put forward in the current, peer reviewed, standard text for fire pattern analysis in the profession, NFPA 921-1995, *The Guide for Fire and Explosion Investigations* were confirmed by the program's testing."

Another series of full scale fire tests were conducted as a result of funding provided by the National Institute of Justice, with a report "Full Scale Room Burn Pattern Study"<sup>7</sup>, released in December 1997. Included in the section of the report, Discussion and Conclusion: "Significant differences in the condition and appearance of the burn rooms and furnishings were present between experiments with the same method of ignition. The differences consisted of the severity of burning, the locations of the patterns, and the types of patterns present. Overall, there was a lack of pattern consistency. As mentioned previously, ventilation effects are the likely cause of the pattern inconsistencies, and should be tightly controlled in future experiments."

The purpose of this paper is to describe the results of the most recent full scale test burns that were conducted at Eastern Kentucky University and sponsored by the Advanced Fire Pattern Project. For the past 2 years a series of eight full scale tests were conducted in identically constructed, finished and furnished compartments. In each of the tests with one exception all fires progressed to full room involvement. Additionally, a full scale test was completed on a specially constructed and furnished room to assist in studying fire growth and spread and the resulting pattern formation in comparison to the fire patterns that were witnessed in a compartment of an actual compartment fire in which there had been a fatality.

These full scale test burns provided a considerable amount of data concerning fire pattern development and evolution during fire growth and spread.

As a result of the previous research conducted into the development of fire patterns, as well as the report recommendations of USFA and NIJ, the Advanced Fire Pattern Research Project (AFPRP) decided to conduct another series of tests. The next series of tests would be conducted in the same test facility with identical furniture for each series of two test burns. Factors, such as ventilation, would be controlled as much as possible. Each of the test burns would be instrumented with thermocouples and documented using 35mm, digital still and video photography.

Recent research into the development of fire patterns has shown that the primary mode behind fire pattern creation stems from the amount of heat flux on a materials surface. Therefore, the plume is the primary means of pattern production in the early stages of a fire. As the fire develops, a substantial upper layer begins to form and starts transferring heat to the wall and ceiling surfaces. This heat transfer can be regarded as relatively universal throughout the upper portions of the compartment, except at the plume interface. Obviously, at the interface of the plume the heat transferred will be greater and for a longer duration.

As the temperature in the upper layer increases and the duration of contact between the upper layer and the wall/ceiling surfaces increases, the heat flux on these surfaces reaches a critical threshold that begins damaging the material and creating patterns. Furthermore, the ceiling jet formed by the intersection of the plume will cause greater heat to be transferred first to the ceiling surface and later to the wall surfaces. The heat flux will be greater at the location where the ceiling jet passes over these surfaces and lessens as the velocity of the jet diminishes as it flows away from the centerline of the plume. In other words, the temperature of the affected surface is hottest near the plume centerline and becomes cooler as the distance from the centerline of the plume increases due to the cooling by heat losses to the ceiling. Thus, inflicting more damage and creating more distinct patterns at the centerline of the plume and lesser damage the further away from the centerline.

The ceiling jet and the gases from the upper layer begin to have a combined effect on the surfaces nearest the plume. As the compartment transitions through flashover and into full-room involvement, the upper layer descends to the floor and encompasses the entire volume of the compartment. Therefore, the walls, ceiling, and floor surfaces are now receiving almost identical heating or a similar magnitude of heat flux. Because of this, some fire investigators often regard the initial plume patterns as being destroyed or obscured. A major part of this research was to determine if the initial plume patterns persist past full-room involvement.

Specifically, these test burns demonstrated fire pattern persistence and predictability during pre and post full room involvement fires. The full scale tests demonstrated that the fire patterns described in current literature are correct and when used properly can assist in the determination of the origin of a fire.

## INTRODUCTION AND SUMMARY OF HISTORICAL LITERATURE

Since the beginning of organized fire investigation, investigators have relied on the examination of building surfaces and the relative damage or change to materials in determining the point of origin of a fire.

Rethoret in his text “Fire Investigations”<sup>1</sup> written in 1945 explains:

“In which direction is the wood carbonized? Study closely the depth of carbonization at various places. Bear in mind that superheated gases spread upwards. This again will assist you in getting back to the point of origin.” (p 36)

“During the course of a fire, substances undergo changes which show themselves in different manners. These changes are characteristic of these substances and, by themselves, furnish valuable leads to the fire investigator.” (p 36)

“The direction of the flames and gases is governed entirely by air currents. Partly burnt wallpaper, the heavy soot deposits previously mentioned, the position of embers, etc., clearly show to the investigator the direction of the air currents.” (p 70)

Many other references to the observation of fire damage to determine the origin of a fire are included in this very early textbook.

In another early text written by John A. Kennedy titled “Fire and Arson Investigation”<sup>2</sup> where in the Cause and Origin chapter he describes the Arrow or Pointer theory.

“A system of determining the point of origin of a fire by tracing its path back to its source was devised by John Kennedy, the author, and is called the “arrow” or “pointer” theory.” .... “In fires involving buildings or other structures where wooden joists or studding are exposed and burning, the application of the fire will usually be constant. The sides exposed to the direction from which the fire is coming will be more severely burned and charred. This will leave a series of burned studs which serve as pointers or arrows to trace the fire” ..... “The investigator who utilizes the “pointer” or “arrow” system of determining the point of origin of the fire will find himself working backwards” (p 286)

Also, in an early text written by Dr. Paul L. Kirk titled, “Fire Investigation”<sup>3</sup> published in 1969, in the chapter titled “Fire Patterns of Structural Fires” he describes fire patterns and how they can be used to determine the point of origin of the fire.

“Every fire forms a pattern that is determined chiefly by the configuration of the environment and the availability of combustible material. Because of the upward tendency of every fire, some of the inverted conical shape is characteristic, the apex at the bottom being the point of ignition, with fire rising and spreading. Naturally, this pattern will be altered by the presence of obstructions, or of readily burned fuel in localized areas.” (p 73)

In the section of this chapter that is titled “Tracing the Pattern” he indicates that “A systematic approach to the study of fire pattern is possible and should be followed.” (p 79)

Given the history of using fire spread and fire pattern analysis, it would be reasonable to believe that the system would also be included in the first edition of NFPA-921, “Guide for Fire and Explosion Investigations”<sup>4</sup>. Contained in Chapter 11, Origin Determination, the following information is provided concerning the use of fire patterns and heat damage in determining the origin of a fire.

**“11-2 Fire Damage Assessment.** Investigators will be making assessments of fire spread throughout the examination of the scene. These assessments include recognizing and documenting heat movement and intensity patterns and analyzing the importance and direction of each pattern found.”

Also, contained in the first edition of NFPA 921 in Chapter 4, Fire Patterns the following information is provided.

**“4-1 Introduction.** One of the major objectives of a fire scene examination is the recognition, identification, and analysis of fire patterns. The analysis of the fire patterns is performed in an attempt to trace fire spread, identify areas and points of origin, and identify the fuels involved.”

Currently, in the 2004 Edition of NFPA 921, “Guide for Fire and Explosion Investigations”<sup>5</sup> similar discussions concerning origin determination and fire patterns are contained.

“17.1.4 The area of origin may be determined by examining the fire pattern evidence of the fire scene. If identifiable, movement and intensity fire patterns should be traced back to an area or point of origin. Once the area of origin has been established, the investigator should be able to understand and document the fire spread. The purpose of determining the origin of the fire is to identify the geographical location where the fire began. When the area of origin has been determined, based on the patterns or any other methodologies set forth in 17.1.1 through 17.1.3, then the specific location of the origin can be identified. The specific origin will be where the heat ignited the first fuel and is commonly referred to as the point of origin.”

“6.1.1 One of the major objectives of a fire scene examination is the recognition, identification, and analysis of fire patterns. The analysis of fire patterns is performed in an attempt to trace fire spread, identify areas and points of origin, and identify the fuels involved.”

The inclusion of the same statements, 4-1 from the 1992 edition and 17.1.4 from the 2004 edition, should be an indication of the importance of understanding the development of fire patterns.

However, as a result of early analysis of the science behind the use of fire patterns and their use in the determination of the origin of a fire revealed that there was little scientific documentation available. As a result, the Advanced Fire Pattern Research Project (AFPRP) was formed in 1985 as a joint research venture by the National Association of Fire Investigators (NAFI) and the Fire and Safety Engineering Technology Program, Eastern Kentucky University (EKU).

### **Advanced Fire Pattern Research Project (AFPRP)**

The AFPRP was founded by the Directors and Instructors of the 1985 Annual Fire Investigation seminar that was being conducted at ECU, and sponsored by NAFI and ECU. Since the formation of the project, considerable work has been undertaken to study fire growth and spread in both full scale and ¼ scale test burns. Much of the data generated has been utilized to supplement instruction in the area of Fire Pattern Analysis. To date, more than seventy full-scale, half-scale, and quarter-scale burn tests have been completed at ECU as a result of the seminars sponsored by NAFI, ECU and later also co-sponsored by the National Fire Protection Association (NFPA). The research burns have enhanced the knowledge base of the fire investigation community.

Separate from the work done by the AFPRP, the National Institute of Standards and Technology, Center for Fire Research obtained funding from the United States Fire Administration to conduct full scale fire tests to study Burn Patterns. This research began in November 1994 with the final report “USFA Fire Burn Pattern Tests”<sup>6</sup> issued in 1997. Included in the summary of results is the confirmation that “many of the concepts, investigative systems, dynamics of pattern production, and patterns analysis concepts

put forward in the current, peer reviewed, standard text for fire pattern analysis in the profession, NFPA 921-1995, *The Guide for Fire and Explosion Investigations* were confirmed by the program's testing."

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## **STATEMENT OF PROBLEM AND GENERAL THEORY**

As a result of the previous research conducted into the development of fire patterns, as well as the report recommendations of USFA and NIJ, the Advanced Fire Pattern Research Project (AFPRP) decided to conduct another series of tests. The next series of tests would be conducted in the same test facility with identical furniture for each series of two test burns. Factors, such as ventilation, would be controlled as much as possible. Each of the test burns would be instrumented with thermocouples and documented using 35mm, digital still and video photography.

### **General Theory**

Recent research into the development of fire patterns has shown that the primary mode behind fire pattern creation stems from the amount of heat flux that is being impinged on a materials surface.<sup>9,10,11</sup> Therefore, the plume is the primary means of pattern production. As the fire develops, a substantial upper layer begins to form and starts transferring heat to the wall and ceiling surfaces. This heat transfer can be regarded as relatively universal throughout the upper portions of the compartment, except at the plume interface. Obviously, at the interface of the plume the heat transferred will be greater and for a longer duration. As the temperature in the upper layer increases and the duration of contact between the upper layer and the wall/ceiling surfaces increases, the heat flux impinging on these surfaces reaches a critical threshold that begins damaging the material and creating patterns. As the compartment transitions through flashover and into full-room involvement, the upper layer descends to the floor and encompasses the entire volume of the compartment. Therefore, the walls, ceiling, and floor surfaces are now receiving almost identical heating or a similar magnitude of heat flux. Because of this, some fire investigators often regard the initial plume patterns as being destroyed or obscured. A major part of this research was to determine if the initial plume patterns persist past full-room involvement.

This series of full scale fire tests were conducted in a manner to address the following problem statements:

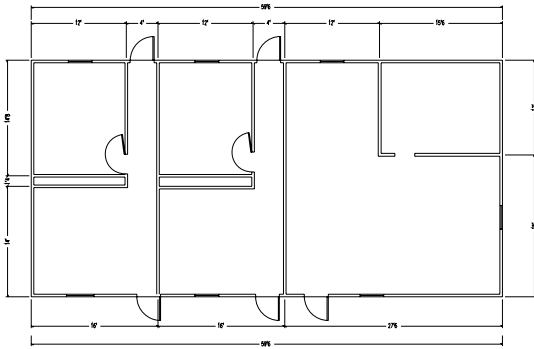
1. Do fire patterns persist through flashover and full room involvement?
2. Can fire pattern geometry be reproducible in minimal variable testing methods?
3. Can standard fire patterns analysis methodologies, such as heat and flame vector analysis, depth of calcination measurement, depth of char, and truncated cone patterns formation and analysis be reaffirmed? As an added value these research burns were designed to test the validity of content of the National Fire Code® component document, *NFPA 921 – Guide for Fire and Explosion Investigations* chapters on Fire Patterns, and Origin Determination.

## **FULL SCALE FIRE TESTS**

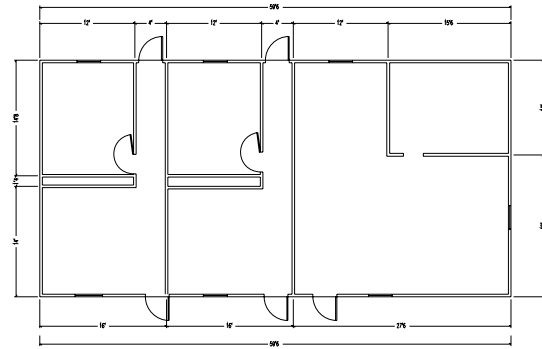
### **The Test Facility**

The test facility used for all these recent experiment sets was the Eastern Kentucky University, Fire and Safety Engineering and Technology Program's test burn building, located on the ECU campus in Richmond, Kentucky. The structure, which opened during the Fall of 2003, is a specially constructed, single story building with overall dimensions of approximately 18.9 m x 9.75 m (62 feet x 32 feet). It

incorporates six interconnected burn rooms and two hallways all with 8" reinforced concrete walls and roof. Individual test cells can be configured into various shapes and sizes by isolating individual spaces with gypsum wallboard partitions (see Figure 1).



**Figure 1: layout of EKU test burn building**



**Figure 2: location of test cells**

### **Fuel Load/ Room Furnishings**

The two test cells located on the north end (left), were originally designed so that identical test burns can be completed at one time.

### **The Test Cells**

The test cells for this research project encompassed the north half of the facility configured into two identical 4.88 m by 9.75m (16' by 32') cells (see figure 2). The cells were constructed of 8" poured, reinforced concrete walls, which were lined with 2x6 joists and gypsum wallboard. All dimensions are approximated.

Rooms with features resembling typical residential bedrooms and living rooms were constructed within the "test burn building". The identical burn cells were composed of a front room 4.87m wide by 4.27m long (~16'W x 14'L) with front door and front window 1.07m wide by 0.91m high (~3'6"W x 3'H); a rear room 3.96m wide by 4.57m long (~13'W x 15'L) with side hallway doorway and rear window 1.07m wide by 0.91m high (~3'6"W x 3'H); and a rear hallway 0.91m wide by 4.88m long (~3'W x 16'L) adjacent to the rear room on the right and leading to a rear exterior door. Exterior doors are 0.99m wide by 2.21m high (3'3"W x 7'3"H).

The bedrooms in both experiments were approximately 4.47m (14'8") long, 4.04m (13'3") wide, and 2.44m (8'0") high. Each room had a single door that was open for the duration of the experiments. The doorways measured approximately 0.91m (3'0") wide, with heights approximately 2.09m (6'8"). The overall dimensions of the window frames were approximately 1.06m (3'6") wide and 0.91m (3'0") high, with the sill or bottom of the window frames located approximately 1.04m (3'5") above the floor. The open area for the window was approximately 0.41m (1'4") wide and 0.76m (2'6") high. All experiments utilized single pane windows.

*Experiment sets "A" and "C":* Experiment sets "A" and "C" (conducted in March 2005 and March 2006) were roughly identical in the layout and types of furniture (Figure 3). The rooms were furnished as typical residential bedrooms and living rooms. The contents of each bedroom included a bed, chest, two lamps, end tables, two nightstands, television (not included in experiment set #3), clothing and a dresser with an attached mirror. The bedrooms had wall-to-wall carpeting on the floor. The contents of each living room included a couch, loveseat, coffee table, two end tables, and television. The living room as well as the hallway had wall-to-wall carpeting on the floor.

*Experiment set "B" and "D":* Experiment set "B" and "D" (conducted in November 2005 and October 2006) was furnished as a residential living room. The living rooms consisted of a couch, loveseat, three

end tables, two lamps and a coffee table. The bedroom consisted of a single mattress with bedding material (Figure 4).

All experiment sets were ignited by the application of a propane torch to a small plastic bag containing a 4"x4" piece of cotton fabric rag doused with about 4 ml gasoline. Experiment sets "A" and "C" were ignited near the head of the bed on the polyurethane bedspread. Experiment set "B" and "D" were ignited near the center of the couch at the base of the vertical cushion.



**Figure 3 Furniture Layout for Experiment Set A & C Figure 4 furniture layout for Experiment Set B & D**

### Instrumentation

The rooms were instrumented for the measurement of temperature with thermocouple arrays strung vertically between the ceiling and the floor (a.k.a. thermocouple trees). Experiment set "A" had two thermocouple trees for each experiment. Each tree was composed of five thermocouples, for a total of ten thermocouples per experiment. The first thermocouple was located at the ceiling height with three thermocouples located at a vertical spacing of approximately 0.15m (6") apart. The fifth thermocouple was vertically located in the center of the room (~4 ft off the ground).

Experiment set "B" had a single thermocouple tree located in the center of the living room. The thermocouple tree had a total of ten thermocouples with a similar configuration as the thermocouple tree from experiment set "A". The last thermocouple for this tree was located at 1.07 m (3.5') off of the floor.

Experiment set "C" had one thermocouple tree inside the bedroom of each test cell. The thermocouple tree consisted of eleven thermocouples with a similar configuration as the previous experiment sets. The eleventh thermocouple was located at 0.92 m (3') off the floor. All experiment sets had a single thermocouple, not associated with the thermocouple tree, located on the ceiling directly above the point of ignition. All thermocouple data was logged and stored electronically at regular intervals of 4 seconds.

Additionally, experiment set "C" had a heat flux transducer placed in each cell. The radiant heat flux at the floor of the bedroom was measured with a water cooled, Schmidt-Boelter type heat flux transducer. The transducer was equipped with a Zinc Selenide (ZnSe) window to exclude convected heat flux. The view of the transducer, with the ZnSe window installed, was approximately 150°. The transducers were installed near the closet of each test cell.

Experiment set "D" had a single thermocouple tree located in the center of the living room. The thermocouple tree had a total of ten thermocouples with a similar configuration as the thermocouple tree from experiment set "A". The last thermocouple for this tree was located at 1.07 m (3.5') off of the floor. Thermocouple 11, was mounted on the wall over the couch.

In addition to the above instrumentation, digital and 35mm still and video photography was used during each test to document the growth and progression of the fire. Photographic records of the compartment fire were supplemented by direct observations and written notes.

### Fire Suppression (Extinguishment) Methodology

During these live fire activities, only IFSAC or PRO Board Certified, experienced firefighters were utilized. Two sources of water supply were provided. The first was a 1985 Seagrave Fire Engine owned by Eastern Kentucky University. This unit is equipped with a 1000 Gallon Per Minute (gpm) pump, supplied with an on-board tank of 500 gallons. One 2 ½ inch line was deployed and split by a gated wye into two 1 ¾” lines, one for fire attack, and the other for a back up line. Also present was a 2001 E-one 75’ aerial provided to us by the city of Richmond fire department. A 1 ¾” hand line was manned by two city employees for emergency situations. Knockdown was accomplished with a fog stream setting, being supplied at 100 psi at the tip. Suppression personnel were instructed to minimize water damage and to focus on the fuel packages themselves. The same firefighters served on the nozzle to ensure duplicate activities for each of the experiment sets.

## TEST BURN RESULTS

### Results – Experiment Set “A” Experiments 1 and 2

In cell #1 (experiment #1), the technical indicator of 600°C (1112°F) in the upper layer for flashover was achieved at approximately 330s (seconds). The duration of the post-flashover/fully involved stage of the fire, the time between flashover and suppression, for experiment #1 was 360 s. In cell #2 (experiment #2), the technical indicator for flashover of 600°C (1112°F) in the upper layer was achieved at approximately 190s. The duration of the post-flashover/fully involved stage of the fire for experiment #2 was 200s. Figure 5 illustrates a timeline for each experiment.

| Experiment #1 Timeline                                                                                                                                                                              | Experiment #2 Timeline                                                                                                                                                                              |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <div> <div>0 s</div> <div>330 s</div> <div>690 s</div> </div> <div> <div>Ignition</div> <div>Flashover</div> <div>Extinguishment</div> </div> <div> <div></div> <div>360 s</div> <div></div> </div> | <div> <div>0 s</div> <div>190 s</div> <div>390 s</div> </div> <div> <div>Ignition</div> <div>Flashover</div> <div>Extinguishment</div> </div> <div> <div></div> <div>200 s</div> <div></div> </div> |

**Figure 5– Comparison of Timelines Experiment Set “A”**

The ventilation conditions for the experiments were expected to differ slightly due to the different locations of the rooms within the test burn building. The differences in ventilation are also suggested by the differences in the temperature growth profiles between experiments #1 and #2. In experiment #1, prior flashover, at 230s a substantial uniform decrease in temperature for all thermocouples was recorded. However, in experiment #2, only a minor decrease in temperature was recorded for all thermocouples just prior to flashover.

A possible reason for the dramatic decrease in temperatures seen in experiment #1 and the resulting differences between the two temperature growth profiles is that the fire in experiment #1 became ventilation-controlled early on during the growth of the fire. This resulted in a decrease in temperature and a subsequent increase in time to flashover. Once sufficient oxygen concentrations returned, the fire quickly grew to transition through flashover conditions and into full-room involvement.

### Results – Experiment Set “B” Experiments 3 and 4

In cell #1 (experiment #3) the technical indicator for flashover of 600°C (1112°F) in the upper layer was achieved at approximately 236s (seconds). Also, in experiment #3, the duration of the post-flashover/fully involved stage of the fire was 124s. In cell #2 (experiment #4) the technical indicator for flashover

of 600°C (1112°F) in the upper layer was achieved at approximately 212s. Also, in experiment #4, the duration of the post-flashover/fully involved stage of the fire was 120s. The temperature growth profiles from experiments #3 and #4 are almost identical. Figure 6 illustrates a timeline for each experiment.

| Experiment #3 Timeline                                                                                                                                                                   | Experiment #4 Timeline                                                                                                                                                                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <div> <div>0 s</div> <div>Ignition</div> </div> <div> <div>236 s</div> <div>Flashover</div> </div> <div> <div>124 s</div> </div> <div> <div>360 s</div> <div>Extinguishment</div> </div> | <div> <div>0 s</div> <div>Ignition</div> </div> <div> <div>212 s</div> <div>Flashover</div> </div> <div> <div>120 s</div> </div> <div> <div>332 s</div> <div>Extinguishment</div> </div> |

**Figure 6 – Comparison of Timelines Experiment Set “B”**

### Results – Experiment Set “C” Experiments 5 and 6

The test in cell #1 (experiment #5) was stopped early due to hazardous weather conditions creating an unsafe work environment. In experiment #5, the technical indicator for flashover of 600°C (1112°F) in the upper layer was achieved at approximately 1396s (seconds). However, the full transition of flashover into full-room involvement did not occur. This was evident from the radiometer readings, as well as the post-fire inspection of the furnishings. In cell #2 (experiment #6), the technical indicators for flashover of 600°C (1112°F) in the upper layer and radiant flux of 20kW/m<sup>2</sup> at the floor were achieved at 790s. The duration of the post-flashover/fully involved stage of the fire for experiment #6 was 215s. Figure 7 illustrates a timeline for each experiment.

| Experiment #5 Timeline                                                                                   | Experiment #6 Timeline                                                                                                                                                                    |
|----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <div> <div>0 s</div> <div>Ignition</div> </div> <div> <div>1396 s</div> <div>Extinguishment</div> </div> | <div> <div>0 s</div> <div>Ignition</div> </div> <div> <div>790 s</div> <div>Flashover</div> </div> <div> <div>120 s</div> </div> <div> <div>1005 s</div> <div>Extinguishment</div> </div> |

**Figure 7 – Comparison of Timelines Experiment Set “C”**

### Results – Experiment Set “D” Experiments 7 and 8

In cell #1 (experiment #7) the technical indicator for flashover of 600°C (1112°F) in the upper layer was achieved at approximately 640s (seconds). Also, in experiment #7, the duration of the post-flashover/fully involved stage of the fire was 194s. In cell #2 (experiment #8) the technical indicator for flashover of 600°C (1112°F) in the upper layer was achieved at approximately 488s. Also, in experiment #4, the duration of the post-flashover/fully involved stage of the fire was 216s. Figure 8 illustrates a timeline for each experiment.

| Experiment #7 Timeline                                                                                                                                                                   | Experiment #8 Timeline                                                                                                                                                                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <div> <div>0 s</div> <div>Ignition</div> </div> <div> <div>640 s</div> <div>Flashover</div> </div> <div> <div>196 s</div> </div> <div> <div>836 s</div> <div>Extinguishment</div> </div> | <div> <div>0 s</div> <div>Ignition</div> </div> <div> <div>488 s</div> <div>Flashover</div> </div> <div> <div>216 s</div> </div> <div> <div>704 s</div> <div>Extinguishment</div> </div> |

**Figure 8 – Comparison Timelines Experiment Set “D”**

## **POST-FIRE ANALYSIS AND PATTERN IDENTIFICATION**

Following each of the fire experiments, the conditions of the room contents and the building components were analyzed. Each experiment was documented by photography, written notes, and diagramming.

Each experiment scene was thoroughly processed using generally recognized and accepted techniques and methods as outlined in NFPA 921 – *Guide for Fire and Explosion Investigations*.<sup>5</sup> Specialized scene processing techniques were utilized including, Depth of Calcination and Heat and Flame Vector Analysis. Scene processing requires special knowledge and skills gained through years of “dirty-knuckles” scene processing. The initial scene evaluation for the research information and documentation was completed by qualified Certified Fire and Explosion Investigators (CFEI’s). After the initial scene processing, the March scenes were then reviewed by those attending the National Advanced Fire, Arson, and Explosion Investigation Science and Technology Program™ as well as students enrolled in FSE-450 Fire, Arson and Explosion Investigation II at Eastern Kentucky University. The November 05 and October 06 scenes were also processed by students enrolled in FSE-495, Fire, Arson, Explosion Case Preparation and FSE-350 Fire, Arson, and Explosion Investigation I. The later groups had not been present during the test burns, but did use fire pattern analysis techniques to determine the area or point of origin and the cause.

### **Scene Processing Techniques: Fire Pattern Analysis**

Two specialized scene processing techniques were employed during the post-fire analysis of each experiment. A depth of calcination diagram and a heat and flame vector diagram were created for each experiment. The methodology for each technique and the resulting diagrams were prepared according to NFPA 921.<sup>5</sup>

*Heat and Flame Vector Analysis:* Each experiment was individually analyzed for all identifiable patterns. A heat and flame vector (arrow) was drawn on the respective diagrams for each pattern to represent the direction of movement (fire spread).

In that the focus of this paper is the persistence of fire patterns post flashover and full room involvement as well as fire pattern reproducibility the complete heat and flame vector analysis will not be reported. That information is contained in a previous paper titled, Full-Scale Room Burn Pattern Study<sup>8</sup>.

## BEDROOM TEST FIRES

Experiment Set A: Experiment 1

March 2005



Experiment Set A: Experiment 2

March 2005



Experiment Set C: Experiment 5

March 2006



Experiment Set C: Experiment 6

March 2006



**Experiment Set A: Experiment 1**

**March 2005**



**Experiment Set A: Experiment 2**

**March 2005**



**Experiment Set C: Experiment 5**

**March 2006**



**Experiment Set C: Experiment 6**

**March 2006**



**Experiment Set B: Experiment 3**

**November 2005**



**Experiment Set B: Experiment 4**

**November 2005**



**Experiment Set D: Experiment 7**

**October 2006**



**Experiment Set D: Experiment 8**

**October 2006**



**Experiment Set B: Experiment 3**

**November 2005**



**Experiment Set B: Experiment 4**

**November 2005**



**Experiment Set D: Experiment 7**

**October 2006**



**Experiment Set D: Experiment 8**

**October 2006**



## DISCUSSION

### General

Given the length limitations of this paper, a decision was made to utilize documentation of each of the test fire origins to demonstrate fire pattern reproducibility as well as fire pattern persistence. The area of origin, by its nature was exposed to the entire duration of the test fire from ignition through flashover and full room involvement. Also, as a result of the length limitation for this paper, inclusion of Thermocouple Data, Heat Flux Data, Depth of Calcination data, and Heat and Flame Vector Diagrams were also not included. This data can be reviewed from a previous paper “Full-Scale Room Patterns Study”<sup>8</sup>. There is extensive data and scene documentation as a part of the Fire Patterns Studies that have been completed during this recent two year project. The data and documentation process has been completed by a variety of individuals, including the researchers, participants in the National Advanced Fire, Arson, and Explosion Investigation Science and Technology Program<sup>TM</sup> as well as students enrolled in classes offered by the Fire and Safety Engineering Technology Program, EKU. Each of the groups participating had varying degree of knowledge and fire investigation experience and they processed the scenes with differing objectives and requirements. However, each group did utilize fire pattern identification and analysis to assist them in completing their objectives.

### Pattern Discussion

#### *Experiment Sets “A” and “C” – Bedroom Ignition*

The post-fire conditions of all room contents (i.e. bed, dresser, chest, etc.) for both experiments were similar. The dresser, chest and nightstands were all deeply charred, but remained primarily intact after the fire. The mattress and bedding were consumed during the fire, except for the metal frame and springs. The exemplar clothing originally hung in the closet was found in a pile at the bottom of the closet area and had been partially consumed during the fire. The plastic components of the television sets for experiment set “A” were consumed or melted away, but the metal components remained. The glass from the bedroom window was broken and no longer present.

Similar truncated cone patterns (i.e. boundary patterns) were witnessed on the walls in all four experiments. The patterns remaining on the hallway walls demonstrate consistency. All four experiments produced a “U-shaped” pattern opposite the doorway on the hallway wall. The only difference that existed was the difference in the pattern vertex between experiments.

Due to its unplanned shortened duration owing to the advent of extreme weather conditions, experiment #5 (experiment set “C”/cell #1) did not transition to full-room involvement before extinguishment. While this was not planned, it serendipitously provided substantial evidence of the early evolution of the patterns. This experiment compared to the other three experiments of similar ignition scenarios, prove that fire patterns existing pre-flashover conditions remain post-flashover. The patterns evolved from distinct lines of demarcation to more subtle lines of demarcation; however, it is evident that the patterns existed both pre- and post-flashover.

#### *Experiment Set “B” and “D” – Living Room Ignition*

Again, the post-fire conditions of all room contents for both experiments were similar. The loss of material patterns for the couch, loveseat, and end tables were very similar. Some of the differences between Sets “B” and “D” could be attributed to the duration of the burns. In all four test fires the ventilation patterns near the doorway were similar. The demarcation lines on the west wall corresponding to the airflow over the loveseat were nearly exact. Located on the east wall above the couch, a conical-shaped plume pattern existed in almost exact appearance between the two experiments. In fact, an almost perfect reproduction of the lines of demarcation remained on each wall behind the couch.

### *Other Patterns*

Effective fire investigators do not rely solely on those large boundary (ie walls, ceilings) patterns as their only means to determining an area of origin. Many times these boundary patterns will lead an investigator to a room or a large volume where further analysis is warranted. It is here that the more subtle patterns lead an investigator to a more defined area of origin or even a point of origin. In all experiment sets there are many identical non-boundary patterns that were observed or measured.

### **Conclusions**

Unlike laboratory bench-top tests (i.e. flash point tests) where variables can be easily controlled, a full-scale room fire test has a wide variety of uncontrollable variables, mostly linked to ventilation. It is rare that full-scale tests can be completely reproducible. The tests reported here show reproducibility well within the parameters that can reasonably be expected. Regardless of the thousands of variables that can affect both fire growth and subsequent pattern formation, similarities in pattern formation between the experiment sets were observed and measured. The most important finding from these tests is that patterns provide substantial evidence for the accurate identification of the correct area of origin.

These tests reaffirmed that fire patterns persist during post flashover conditions, as well as provide evidence of the evolution of these fire patterns. This research revealed that the initial plume patterns are not lost, in fact, the experiments presented here have shown that the demarcation lines or initial patterns formed by the plume persist after flashover (See Experiment #5 Discussion Above). The research shows that these patterns do begin to evolve from the sharp distinct demarcation lines into more subtle demarcation lines due to the descending upper layer and its resulting damage. However, the initial plume patterns are still present and have been reliably shown to assist in determining an area of origin.

Additional research is needed and as of this time, the Advanced Fire Pattern Research Project does have plans to expand the scope of the current research. Changes will include moving the origin, analysis of the persistence of patterns well after flashover, analyzing the patterns that remain after igniting a small fuel next to a large fuel and analyzing whether a reliable origin can be determined; the use of FDS/Smokeview in analyzing fire patterns, and the addition of ignitable liquids to the ignition scenario.

## ABOUT THE AUTHORS

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## END NOTES

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