ADVANCED FIRE PATTERN RESEARCH PROJECT: SINGLE FUEL PACKAGE FIRE PATTERN STUDY

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ABSTRACT

Several studies have been completed in the creation of and documentation of various fire patterns. However, no study had sought to prove the reproducibility of the fire patterns used for fire scene investigations. Although some of these studies have been subjected to peer review, the purpose of this research was to quantify the reproducibility of fire patterns used by investigators in the determination of origin and cause, and to provide support for the contents of NFPA 921-*Guide for Fire & Explosion Investigation*. This study focused on the development of three recognized pattern formations: Triangular (Inverted cone), Columnar, and Conical. Specifically, this study researched the development of these pattern formations on standardized witness surfaces (drywall panels) during the combustion process of a standardized fuel package (wood cribs). This study showed that although the time to reach the pattern differed, the amount of mass consumed and heat produced by the fire, along with the ignitability of the witness surface and the heat energy imparted on the receiving surface were the decisive factors in reproducing a consistent, similar pattern. This study was intended to place a foothold below an existing study titled Full Scale Room Burn Pattern Study, which was also seeking to validate the reproducibility of fire patterns. This current study illustrates that similar fuel packages will reproduce a similar pattern in a controlled environment.

INTRODUCTION

For the last sixty years fire patterns have been used to determine the origin of fires in every setting imaginable. Although initially lacking scientific support, and being attached to some "Old Wives' Tales", fire pattern interpretation remains an essential part of the investigative process. Several studies have been done to establish the various states or forms that fire patterns take which included studies concerning ignitable liquids and commonly found residential fuel packages.

Among the existing literature, there are no studies that assign a series of tests solely for the purpose of determining the ability of fire patterns to be recreated under controlled conditions.

This study is a continuation of a separate ongoing study using full-scale rooms similar to the ones done in the studies discussed in the literature review section. These test burns consisted of three pairs of identical burns called experiment sets. One such scenario was a set of bedroom suites (experiment set “A”), which were burned in March, 2005 as part of the National Advanced Fire Arson & Explosion Investigation Science and Technology Seminar held at Eastern Kentucky University, in conjunction with the National Fire Protection Association (NFPA) and the National Association of Fire Investigators (NAFI). The second set (experiment set “B”) were constructed as residential living rooms, which were furnished with duplicate items, had similar burn times, and were ignited in the same location. These were burned in the fall of 2005 as part of the EKU Fire and Explosion Investigation II course. Both Burns showed very similar fire patterns, with some different effects being attributed to ventilation. This project continued with duplicate bedroom burns (experiment set “C”) during the 2006 National Advanced Fire Arson & Explosion Investigation Science and Technology Program, also held at EKU. These burns also exhibited similar fire pattern production, but the effects of ventilation still caused some turbulent air entrainment and expulsion from the test cells.

The researchers realized that in order to fully quantify the nature of fire pattern development as being reproducible, a more controlled environment should be used. To achieve a more controlled and reproducible test environment, a standardized and reproducible scale fuel package would have to be used. Therein, creating a better characterized fire for a controlled experiment, which is important for any future research.

The three plume shapes referenced below are listed in NFPA 921 as indicators of fire conditions that were exhibited from a single fuel package. The flame zone pattern produced is indicative of the heat and products of combustion, and are used in analysis of the fire scene. The pattern imparted by the flame plume generally has five variables. The first variable is the amount of heat released and the time over which it was released (heat release rate). The second is the effects of ventilation, and its influence on pattern production, by allowing heat and byproducts to escape the compartment. Third, witness surface characteristics, such as the thermal inertia, non-combustion responses to heating, ease of ignitability and combustibility of the surface being exposed to the burning fuel package also influence fire pattern production. The fourth variable addresses the effects of any intersecting surfaces, and their characteristics, can also play a role in pattern development. The final variable is the fuel packages proximity with the witness surface. However, as these variables are overcome, the pattern that is produced goes through a series of steps in its evolution. It should be noted that this study focused on one type of combustible witness surfaces. Noncombustible witness materials will have differing witness surface characteristics.

Triangular Pattern

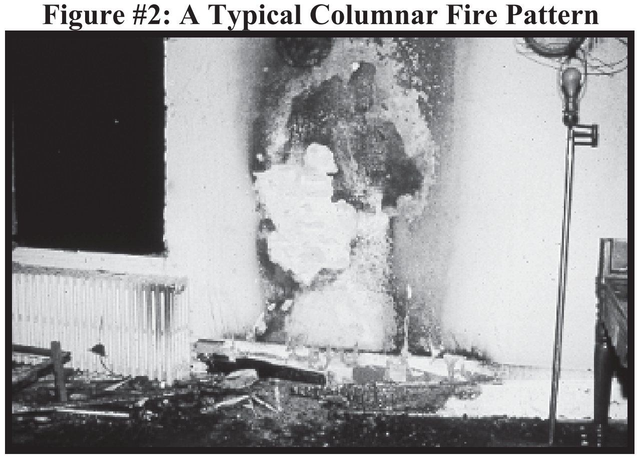
The first pattern under consideration is an inverted cone, or triangular pattern. The inverted cone or triangular pattern resembles an upright triangle with the vertex at the top. This flame zone pattern is associated with a fuel package that has the potential heat release rate to overcome the thermal inertia and start a pyrolysis reaction in the witness material, thereby creating the pattern, but insufficient to produce a plume which reaches any horizontal restriction above the fuel package. However, due to several possible variables, such as the fuel package being extinguished or the heat being diverted, the damage done to the surface material is limited to the area immediately adjacent to the flame plume producing the radiant heat. This leaves a visible area that exhibits heat exposure having a sharp leading edge of demarcation, which widens significantly at the base forming a triangular shape or pattern.

Figure 1: A Typical Triangular Fire Pattern (NFPA 921)

Columnar Pattern

A columnar flame zone pattern is characterized by largely parallel vertical lines of demarcation and a heat release rate sufficient to reach any horizontal restriction above the fuel package. A columnar pattern is a visible pattern where the leading front, or sharp leading edge of demarcation from a triangular pattern, has continued to spread with the rising heat and other products of combustion, and has reached an intersecting horizontal surface. This causes the heat and byproducts of combustion to begin spreading along the intersecting surface and, depending on the size of the compartment, bank down (descend) to create a ceiling layer, which provides the "cap" of this pattern. This pattern is generated by the increasing convective heat exposure to the surface above the fuel package. This process continues until the fuel package is consumed, or is controlled by one of the many other variables.

Figure #2: A Typical Columnar Fire Pattern



Conical Pattern

A conical flame zone pattern is produced when the interacting buoyant fire plume is restricted by an intersecting horizontal surface, spreading the heat across the bottom of the obstructing surface (ceiling jet) thereby widening the horizontal area of exposure at the top of the pattern. This results in a pattern that resembles a funnel or cone with the vertex at the bottom. This pattern is indicative of a fuel package that has produced a heat release rate sufficient to create a plume that reaches the horizontal obstructing item.

Figure #3: A Typical Conical Fire Pattern

LITERATURE REVIEW

Several studies have been conducted to help identify the patterns in compartment fires produced as fuel packages evolve from ignition, reach a steady state, and go thru decay.

In 1994/1995 The United States Fire Administration, in conjunction with the National Institute of Science and Technology, Building and Fire Research Laboratory (NIST-BFRL) launched the fire pattern research committee and produced the USFA Fire Pattern Test report, authored by Kennedy and Shanley, July 1997.[1] This project consisted of 10 separate full-scale burns to produce the first scientifically controlled and recorded research into the formation, growth, and investigation of patterns produced in fires. These tests produced the first data that supported patterns as being useful in fire investigation. This study also noted that ventilation was one of the most prevalent variables, having the influence to alter or hinder normal pattern production. This set the stage for a series of tests in the documentation of the patterns produced in a fire.

In June of 1996, two full-scale room fire experiments were performed by Milke & Hill at the University of Maryland.[2] The purpose of these tests was to see if duplicate pattern formations would evolve from duplicate fuel packages, with a similar ignition point. This resulted in unspecified differences that were attributed to ventilation.

In March of 1997, McGarry & Hill, in conjunction with the University of Maryland, continued the full-scale room experiments.[3] Two full-size furnished bedrooms were burned at the University of Maryland Fire Rescue Institute Facilities. It was intended that these two burns be identical, to determine if close analysis of the results would discover differences. In both cases, ignition of a gasoline spill next to an upholstered chair was used to initiate the fire. The researchers noted differences, and again attributed these to small variations in the inflow of ventilation air.

In December 1997, a full scale room burn pattern study was conducted by Putorti at the University of Maryland Fire Rescue Institute.[4] This study consisted of four full-scale compartments with similar furniture and flooring, but with two different ignition scenarios (accelerated and non-accelerated). The conclusions of this study were that, while many similarities existed, some differences occurred which were the result of variables beyond control, such as ventilation, oxygen content and the number of experiments conducted. The results were considered inconclusive by the author who called for further study.

TEST PROCEDURES

Location

All burns in this study were conducted at Eastern Kentucky University's Fire and Explosion Building, located in Richmond, KY. This Building contains a configurable floor plan, with a fixed width American Society for Testing and Materials (ASTM) fire test room for such fire experiments. The burn cells discussed later in the procedures were set up inside this room.

Ventilation

In almost all previous studies, ventilation was mentioned as being a varying factor affecting the production of patterns. By building a test cell inside of one of the Burn Building burn rooms, we were able to control the flow of air and limit its effects upon the flame movement. This resulted in a test environment that could be reproduced without extravagant measures or large sums of money, yet allowing us to alleviate much of the air movement that would divert the natural convective patterns produced by the fuel package itself.

Photography & Film

Digital photographs were taken of all the activities. Photographs were taken of each burn prior to and immediately after each burn to document the pattern created. Each panel of drywall was retained and photographed after removal and during depth of calcination studies, with the exception of the conical burns. The conical burns were documented in place prior to removal.

Video was recorded using a Digital Video Camera. This film was transferred over to Digital Video Disk. Video of each test burn and several of the protocol burns was retained. During columnar Burn #2 a power interruption occurred which caused the footage being taken to be lost.

Depth of Calcination

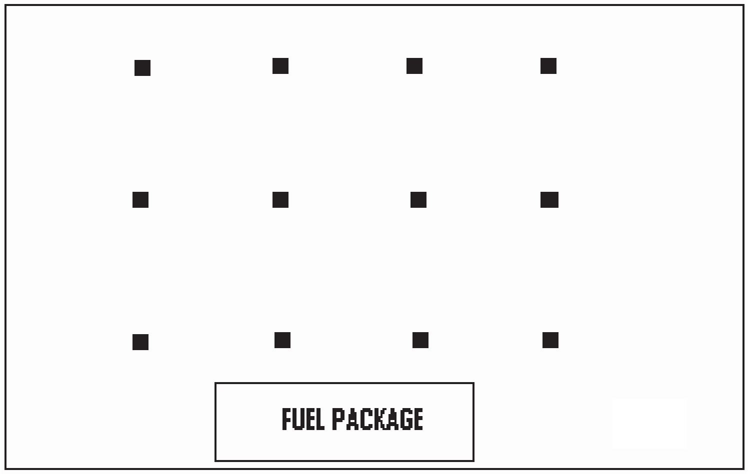
Depth of calcination studies of both the triangular and columnar tests are being performed at this time. Each panel was removed, and the survey performed by a depth caliper with a blunt ended probe. All surveys were performed by the same team to ensure comparable results. This information was documented and graphed and transferred to a spreadsheet. Due to time constraints, these findings were not able to be included with this paper.

A depth of calcination survey of the conical tests was performed with the drywall in place, due to the delicate nature of the rear wall. However, all panels were photographed prior to being removed from the test cell.

Burn Cell

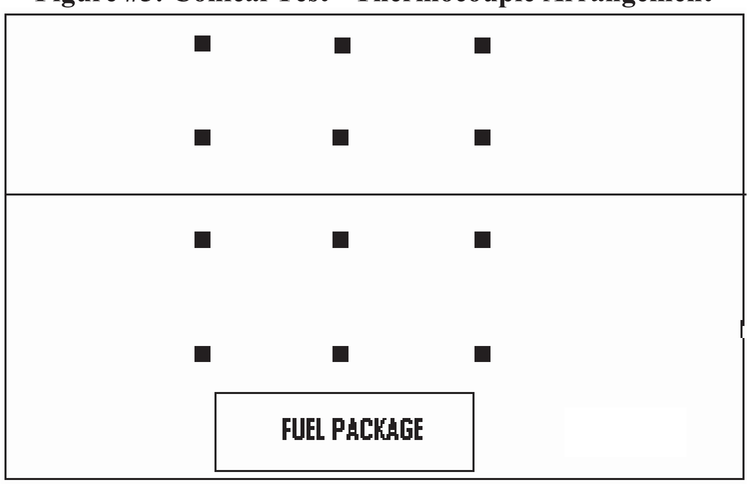
The burn cell for the Triangular and Columnar burns was constructed of 2x4 members, configured to be a 4'x4'x4' cell, with 3/8 inch thick drywall walls and double layered ceilings. One side remained open to facilitate observations. The rear wall of the cell was covered with 3/8 inch drywall which was prepared with twelve holes drilled for thermocouples (six inches between each hole, vertical and horizontal, see fig. 1). These were centered in the 4'x4' sheet and off set every six inches to facilitate entry of thermocouple probes. This sheet was replaced after every burn, documented and saved for the depth of calcination study.

Figure #4: Triangular and Columnar Burn Tests - Thermocouple Arrangement



The burn cell for the conical patterns was similar to the one mentioned above, with dimensions being 6'x6'x6'. This cell was also lined with 3/8 inch drywall, with doubled ceilings. The sheet was predrilled with holes for thermocouple probes to be inserted as the rear wall. These were staggered eighteen inches from the sides and bottom, then spaced twelve inches apart horizontally, and spaced six inches vertically, forming three rows of four (Figure 2).

Figure #5: Conical Test - Thermocouple Arrangement



Fuel Package

Research was conducted to identify a recognized scale fuel package that would facilitate the goals of this research project. It was decided to utilize the American National Standards Institute/Underwriters Laboratories (ANSI/UL) Wood Crib for testing of 1-A fire extinguisher rating as a base design. These cribs were made of what is commonly termed Spruce-Pine-Fur (SPF), available at most larger home repair stores. This allowed for a peer recognized and easily reproducible wood crib to be built. The 1-A crib is constructed of 50 cross sections of 1.5" x 1.5" x 20" pieces of wood configured in 10 layers of 5 cross members. Each piece of wood was nailed with a 16 gauge finish nail, weighing .8 grams, with 48 nails in every ½-A crib. Finished crib weights varied due to wood density. Early on it was decided to use a 5 layer with 5 cross members per layer crib to allow for more of a controlled environment. This gave a scaled down crib size with an approximate rating of .5 or ½ A. Although these board members came from a sealed, contractor package, they were assembled and allowed two weeks to season, or achieve consistent moisture content.

Protocol Burns

Protocol burns were conducted to determine at what point (loss of mass) in each fuel package the various patterns were produced. The first burns were allowed to continue through to the late decay stage of the fire in order to better assess the point at which each pattern was produced. Early on it was noted that there was not a high enough heat release rate to develop a conical pattern using on scaled burn crib. During these burns a specific loss of mass was recognized for the triangular and columnar patterns being produced. Upon completion of the first two series, another protocol burn was initiated to attempt to reach a conical pattern. This test used a full 1-A crib in hopes of producing and establishing a reproducible conical pattern. This test completely overwhelmed the 4'x4'x4' test cell, and the test had to be stopped due to fire spreading to the cell itself. We then moved to a 6'x6'x6' test cell. A second protocol burn was done with a 1-A crib, which resulted in a columnar pattern. A third protocol burn was performed. To expand the heat release potential, and develop a conical pattern, a third scaled burn crib was added to the scenario, by placing two scaled cribs side by side with the third crib being placed center upon the two, forming a pyramid shape. This fuel package was allowed to burn to completion. During this test burn, a definable conical pattern was achieved and the mass consumption relative to the point of pattern production was noted.

Surface Materials

Standard grade, 3/8 inch drywall was used for these test cells. This surface material was chosen because it is the most commonly used interior finish for all types of structures. This drywall was purchased and allowed to season for two weeks to ensure each piece held similar moisture content. It was secured to the test cells by 1 ½ inch course drywall screws.

Weight Measurement

Weight measurements were obtained by a commercially available load cell. This load cell was protected by insulation and drywall pieces cut to fit the top of the scale. These weights were tarred (set to zero) each time a new test was performed. The measurements were obtained in ounces, as this was the smallest measurement scale available.

Ignition

Ignition was provided by 14 ounces of 89 octane gasoline, which was poured into a 3 x 4 inch plastic evidence bag that contained one roll of gauze bandage in order to control the ignitable liquid and prevent it from flowing unpredictably. The ignition source fuel package was then placed in a central location of the wood crib. For the columnar and triangular burns, a single ignition source fuel package was used. During the conical burns, 2 ignition source fuel packages were used to achieve an even ignition of the wood cribs.

Temperature Measurement

All test burns were monitored with thermocouples, set to log temperature measurement units in Celsius. This data was collected in Excel spreadsheets and later converted into a line graph form. During each burn, twelve thermocouples were used with different configurations for each series (see figures 4 & 5). During the columnar and triangular burns, 4 rows, spaced six inches apart, both vertically and horizontally, were used. During the conical burns, three rows of four were used, with the spacing being 1 ½ feet both horizontally and vertically. Thermocouple probes were changed out after each test to ensure proper function.

Heat Release Rate Calculations

The average heat release rates (theoretical) for each test burn was calculated for further analysis and comparison. The theoretical heat release rate equation has been provided in figure 6.[5] Note that the effective heat of combustion for wood, which includes many different types of wood species, is approximately 13MJ/kg.[6] We have provided a basis for the average heat release rates achieved during each test burn by utilizing this effective heat of combustion coupled with the mass loss rate gathered from the experimental data. The calculation results have been provided in table 1.

Figure 6: Theoretical Heat Release Rate Equation

Heat Release Rate Equation	
$HRR_{avg} = \Delta h_{c,eff}$ x MLR	$\dot{q} = \Delta h_{c,eff} \times \dot{m}$
Where: HRR – Calculated Average Heat Release Rate $\Delta h_{c,eff}$ – Effective heat of combustion MLR – Mass Loss Rate (mass/time)	$\dot{q}$ - heat release rate (kW) $\Delta h_{c,eff}$ – heat of combustion (MJ/kg) $\dot{m}$ - mass loss rate (kg/s)

RESULTS

This study was able to reproduce similar patterns given standard fuel packages. By conducting a protocol burn and noting mass loss associated with certain pattern phases, the researchers were able to reproduce similar patterns (see photo series starting on page). During the protocol burns, the established pattern point, or the point at which enough heat was imparted onto the surface by the flame plume to produce a visible pattern was reliably determined. The triangular pattern point was set at a consumption of 90 ounces of the fuel package. The columnar pattern point was set at 200 ounces, and the conical pattern point was set at 545 ounces. Table 1 lists the starting mass for each crib, the mass loss required for the pattern being produced, and the time of the burn. This research was able to show that flame zone patterns can be reproduced using the same fuel package (moisture level, etc) by controlling the amount of mass consumed during the combustion process.

A range of calculated heat release rates for each burn pattern formation is shown in table 1. The low and high heat release rate values (extremes) for each range were dropped to refine the ranges. The triangular pattern formation has an average heat release rate range between 24kW and 42kW. The columnar pattern formation has an average heat release rate range between 55kW and 69kW. The conical pattern formation has an average heat release rate range between 136kW and 228kW. There is an apparent split in the range values between each pattern formation.

Table 1-Mass Loss and Burns Times

BURN	START WEIGHT - Oz (kg)	TARGET MASS LOSS – Oz (kg)	TIME - Min (sec)	EXTINGUISHEMENT WEIGHT – Oz (kg)	Average Heat Release Rate (HRR)
	TRIANGULAR				
1	333 (9.44)	90 (2.55)	11:37.6 (697.6)	243 (6.89)	47.60
2	330 (9.36)	90 (2.55)	22:16.0 (1336)	240 (6.80)	24.80
3	313 (8.87)	90 (2.55)	13:04.4 (784.4)	223 (6.32)	42.26
4	323 (9.16)	90 (2.55)	18:44.0 (1124)	233 (6.61)	29.49

5	326 (9.24)	90 (2.55)	14:58.8 (898)	236 (6.69)	36.91
6	335 (9.49)	90 (2.55)	15:26.7 (926.7)	245 (6.95)	35.77
7	324 (9.19)	90 (2.55)	16:55.3 (1015.3)	234 (6.63)	32.65
8	329 (9.33)	90 (2.55)	15:17.0 (917)	239 (6.78)	36.15
9	324 (9.19)	90 (2.55)	18:06.6 (1086)	234 (6.64)	30.50
10	330 (9.36)	90 (2.55)	19:59.0 (1199)	240 (6.80)	27.65
11	342 (9.69)	90 (2.55)	24:59.0 (1499)	252 (7.14)	22.11
12	339 (9.61)	90 (2.55)	15:25.3 (925.3)	249 (7.06)	35.83
13	326 (9.24)	90 (2.55)	14:00.6 (840.6)	236 (6.69)	39.44
14	326 (9.24)	90 (2.55)	15:21.3 (921.3)	236 (6.69)	35.98
15	338 (9.58)	90 (2.55)	14:54.7 (894.7)	248 (7.03)	37.05
16	334 (9.47)	90 (2.55)	13:35.0 (815)	244 (6.92)	40.67
17	330 (9.36)	90 (2.55)	13:17.6 (797.6)	240 (6.80)	41.56
18	334 (9.47)	90 (2.55)	14:04.0 (844)	244 (6.92)	39.28
19	327 (9.27)	90 (2.55)	17:00.2 (1020.2)	237 (6.72)	32.49
20	330 (9.36)	90 (2.55)	16:29.3 (989.3)	240 (6.80)	33.51
					Range: 24-42
	COLUMNAR				
1	321 (9.10)	200 (5.67)	20:55.0 (1255)	121 (3.43)	58.73
2	323 (9.16)	200 (5.67)	DATA LOST	123 (3.49)	--
3	333 (9.44)	200 (5.67)	24:59.0 (1499)	133 (3.77)	49.17
4	332 (9.41)	200 (5.67)	19:25.3 (1165.3)	132 (3.74)	63.25
5	338 (9.58)	200 (5.67)	21:40.0 (1300)	138 (3.91)	56.70
6	320 (9.07)	200 (5.67)	22:10.0 (1330)	120 (3.40)	55.42
7	321 (9.10)	200 (5.67)	20:40.3 (1240.3)	121 (3.43)	59.43
8	320 (9.07)	200 (5.67)	21:57.8 (1317.8)	120 (3.40)	55.93
9	321 (9.10)	200 (5.67)	19:51.3 (1191.3)	121 (3.43)	61.87
10	331 (9.38)	200 (5.67)	20:35.7 (1235.7)	131 (3.71)	59.65
11	339 (9.61)	200 (5.67)	20:25.0 (1225)	139 (3.94)	60.17
12	323 (9.16)	200 (5.67)	21:18.0 (1278)	123 (3.40)	57.68
13	330 (9.36)	200 (5.67)	18:34.6 (1114.6)	130 (3.69)	66.13
14	326 (9.24)	200 (5.67)	20:50.7 (1250.7)	126 (3.57)	58.93
15	326 (9.24)	200 (5.67)	17:50.6 (1070.6)	126 (3.57)	68.85
16	322 (9.13)	200 (5.67)	21:47.4 (1307.4)	122 (3.46)	56.38
17	327 (9.27)	200 (5.67)	22:05.3 (1325.3)	127 (3.60)	55.62
18	322 (9.13)	200 (5.67)	17:45.6 (1065.6)	122 (3.46)	69.17
19	326 (9.24)	200 (5.67)	16:51.6 (1011.6)	126 (3.57)	72.86
20	334 (9.47)	200 (5.67)	18:06.0 (1086)	134 (3.79)	67.87
					Range: 55-69
	CONICAL				
1	995 (28.21)	545 (15.45)	18:55.0 (1135)	450 (12.76)	176.96
2	975 (27.64)	545 (15.45)	15:13.7 (913.7)	430 (12.19)	219.82
3	971 (27.53)	545 (15.45)	16:15.7 (975.7)	426 (12.08)	205.85
4	1022 (28.97)	545 (15.45)	17:35.4 (1055.4)	477 (13.52)	190.31
5	1042 (29.54)	545 (15.45)	24:27.4 (1467.4)	497 (14.09)	136.87
6	1062 (30.11)	545 (15.45)	21:08.5 (1268.5)	517 (14.66)	158.34
7	1012 (28.69)	545 (15.45)	14:37.7 (877.7)	467 (13.24)	228.84
8	1057 (29.97)	545 (15.45)	19:49.4 (1189.4)	512 (14.52)	168.87
					Range: 136-228

DISCUSSION

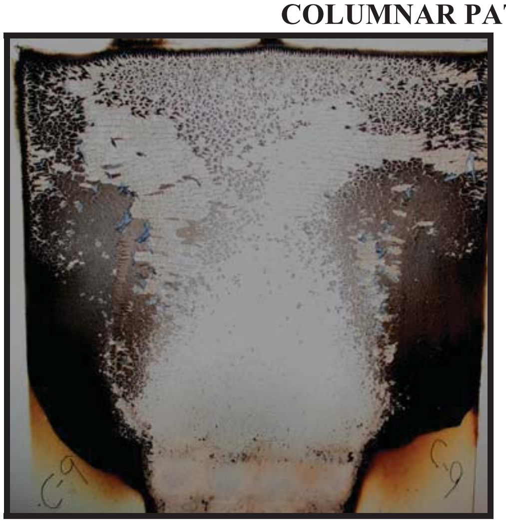
This study showed that when the 5 controllable factors (heat release rate, ventilation, witness surface characteristics, intersecting surfaces, and fuel packages proximity) are limited, a similar, duplicate staged pattern occurs. Although recreating the exact conditions present on a fire scene, including: obtaining the same fuel package and achieving exact duplication of the conditions present at the time of the fire would be difficult, this study illustrates that the evolution of flame zone pattern phases that a fuel package goes through during a fire are valid, and have now been tested in a controlled environment. By controlling the air movement (not Oxygen concentration) these researchers were able to limit any air movement effects on pattern production.

TRIANGLE PATTERN PHOTOS

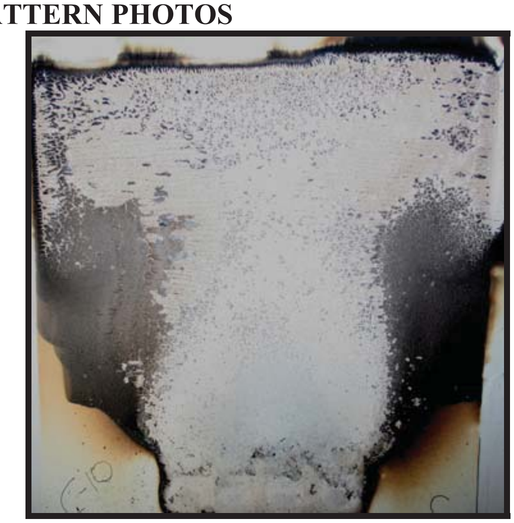
Triangle Pattern #17

Triangle Pattern #20

COLUMNAR PATTERN PHOTOS

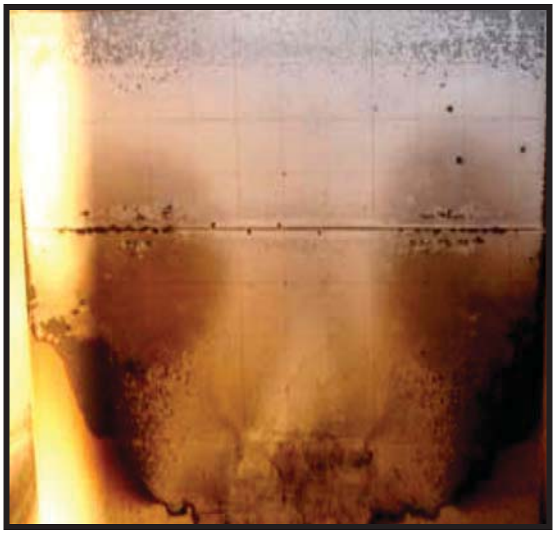


Columnar Pattern #9



Columnar Pattern #10

CONICAL PATTERN PHOTOS


Conical Pattern #1


Conical Pattern #8

ABOUT THE AUTHORS

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END NOTES

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[2] Milke, J.A., and Hill, S.M. "Full-Scale Room Fire Experiments Conducted at the University of Maryland.", NIST GCR-96-703, National Institute of Standards and Technology, October 1996.

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