Fire Patterns Analysis with Low Heat Release Rate Initial Fuels

ABSTRACT
The science behind the formation of fire patterns and their ensuing use in the forensic analysis of fire scenes has been questioned since their introduction in the 1940's. One key argument against the use of fire patterns, especially in post-flashover fires, is that they will be obscured beyond use by higher heat release rate items or by full-room involvement. This study addresses this concern by evaluating the persistency of these patterns in several scenarios. This experimental series consisted of 24 full-scale tests involving a variety of initial fuels and room configurations. Two representative tests are presented here. All of the tests completed were allowed to transition through flashover and burn in the post-flashover regime for a limited duration. It was the focus of this research to obtain a baseline for the resulting post-flashover patterns with the intent of studying longer duration fires in future testing. All tests in this study yielded enough evidence to accurately and reliably reach the correct area of origin and supported that fire patterns will persist regardless of the initial fuel package. It should be noted here, however, that these findings should not be extrapolated to all fires. With proper documentation of the scene and a sound knowledge of fire dynamics, an investigator was able to reach appropriate conclusions regarding the origin of the fire utilizing fire patterns in this test series.

Keywords: fire patterns, fire effects, compartment fires, fire investigation

INTRODUCTION

Fire investigation plays a critical role in identifying potentially faulty or improperly designed and installed products, which may have played a role in the fire, and in identifying persons that deliberately started a fire with malicious intent. In the end, proper fire investigation should determine the fire cause, the cause of the resulting property damage, and most importantly, the cause of bodily injury or loss of life to civilians and firefighters. To meet this objective, an accurate cause assessment is essential, and an accurate cause assessment depends on an accurate origin determination. Therefore, correct identification of the origin of the fire is the scene investigator's most important hypothesis.

Since the beginning of organized fire investigation in the late 1940's, fire investigators have relied on burn patterns as a basis for determining the fire origin [1]. Fire patterns are defined as the "visible or measurable physical changes, or identifiable shapes, formed by a fire effect or group of fire effects" [2]. Absent the testimony of reliable eyewitnesses to the fire's inception, the investigator is often required to determine the origin by observation and expert interpretation of the physical evidence (i.e. the fire patterns). As such, fire origin determination is largely a matter of fire pattern recognition and analysis [2].

DYNAMICS OF FIRE PATTERN DEVELOPMENT

When a fire develops in a compartment, the products of combustion (i.e. heat, soot) begin to influence the materials within the compartment. Consequently, the lining materials for the walls, ceiling, and floor, as well as the various contents within the compartment, are damaged by their exposure to the products of combustion. The variety of damage to these objects is collectively known as *fire effects*. NFPA 921 defines fire effects as "the observable or measurable changes in or on a material as a result of exposure to the fire" [2]. The degree to which materials are influenced by the developing fire will be a function of the material characteristics, intensity of the products of combustion, and the duration of exposure. The grouping of fire effects provides an indication of fire travel, intensity, and/or duration. This collection of fire effects or trends in the data is what is known as fire patterns. The challenge for the fire investigator is to correctly interpret the fire effects to determine their relationship to indicate fire travel, intensity, and/or duration to isolate the area or origin, despite the uncertainty associated with the interpretation of the effects.

General Theory

Recent research into the development of fire effects has shown that the primary mode behind fire pattern creation is the total heat flux to a materials surface throughout the duration of the fire, also thought of as the cumulative heat flux [5-13]. Therefore, the sources of heat flux during a compartment fire must be considered when evaluating the post-fire damage. As heat transfer is first and foremost dependent on a temperature difference, the greater temperature differences will result in the greater heat flux. In a compartment fire, the highest temperatures are present at those locations where flaming combustion is taking place. The fire plume and the various heat fluxes generated by it are one of the primary means of damage production in the early stages of a fire due to this great temperature difference and highly turbulent flows. Fire plumes against wall surfaces have heat fluxes ranging from 40-80 kW/m^2, while heat fluxes measured in tests with objects immersed in diffusion flames range between 75-200 kW/m^2 [14-16]. Incident heat flux is dependent on the heat release rate of the fuel and standoff distance between the plume and the surface of interest.

Any 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 temperature of the plume will be greatest near the plume centerline and therefore the greatest heat flux to the ceiling surface will be at this location. The temperature and resultant heat flux lessens with increasing distance from the plume centerline. In addition, the ceiling jet velocity is highest near the centerline of the plume and decreases as it moves outward [19]. Consequently, these two factors combine to inflict more damage and create more pronounced fire effects near the plume centerline, with the damage decreasing as the distance from the centerline is increased. Heat fluxes along the ceiling surface have been recorded to range between 80-100 kW/m^2 near the centerline of the plume within 0-1 meter radial distance and range between 10-70 kW/m^2 between 1-1.6 meter radial distance from the centerline of the plume [15, 17].

As the fire continues to develop, the ceiling jet and the gases from the upper layer begin to have a heightened effect on the surfaces nearest the plume. Later in a fire's development, an upper layer begins to form and starts transferring heat to the wall and ceiling surfaces. The energy generated by the fire and therefore the temperatures and layer depth of the upper layer vary as a function of time [21]. Thus, different locations within the compartment may be receiving different temperatures at different times throughout the fire. However, an assumption can be made for fuel-controlled fires, that higher temperatures will occur at the plume interface with any building or contents surface. As the temperature of the gases in the upper layer increases and the duration of influence between these gases and the lining surfaces increase, the heat flux imposed on these surfaces reaches a critical threshold that begins damaging the material and creating fire effects attributed to the hot gas layer. Heat fluxes to the walls inside a compartment containing a hot gas layer have been reported to range between 5-40 kW/m^2, based on varying temperatures [18].

As the compartment transitions through flashover and into full-room involvement, the upper layer descends to the floor and encompasses nearly the entire volume of the compartment. Therefore, the walls, ceiling, and floor surfaces are now receiving an elevated heat flux. The maximum recorded heat flux in a post-flashover compartment fire is 170 kW/m^2 [2].

During the transition through flashover, a fully involved compartment fire, and/or when a compartment fire is ventilation-controlled, more complete combustion is achieved at those locations where the fuel/air mixture is adequate. This burning is often times disassociated from a fuel item (i.e. wood chair) and the pyrolyzates (unburned fuel) will burn in locations near ventilation openings and along airflow paths [4, 8-12]. Consequently, temperatures in the upper layer will also vary based on local variations in the air/fuel mixture. A substantial degree of damage is often times found directly adjacent to or opposite of window and door openings. This type of damage was first noted in the USFA study with specificity and has been recognized as a major factor by educated fire investigators since 1997 [4, 8].

The effects that remain after a fire are related to the cumulative heat flux received by an exposed material and therefore is paramount that investigators recognize the difference between the factors of duration and intensity when analyzing the damage against the compartment fire dynamics. Many of these factors have been pointed out in other fire patterns research [3-13, 22]. Yet still, there are many fire investigators that fail to take all of the available research and implement into practice the concept of identifying areas of damage in relationship to the compartment fire dynamics. Consequently, there are several factions emerging on the use of fire patterns. Some fire investigators often regard the initial plume effects as being destroyed or obscured after a fire transitions to full-room involvement or when higher heat release rate fuels become involved. Thus, negating the use of fire patterns to arrive at an area of origin in fully involved compartment fires or fire scenarios that involve multiple fuel packages. Other investigators, regardless of the factors influencing fire dynamics, interpret the area of greatest damage as being the area of origin. Neither approach is appropriate based on the available research. The effective fire investigators are combining the available fire patterns research with compartment fire dynamics to implement those concepts into their analysis to arrive at more accurate and scientifically defensible results [29].

PURPOSE

A frequent question that arises in fire patterns analysis is whether the initial damage caused by a lower heat release rate fuel persists after the involvement of a significantly higher heat release rate fuel. For example, will the initial damage or patterns from a fire originating in a wastebasket (~50-100 kW) directly adjacent to a polyurethane foam sofa (~2,000-3,000 kW) persist or be obscured post fire? More importantly, will the damage persist to the point where fire investigators can effectively use the remaining data to arrive at an accurate origin?

The purpose of this test series was to evaluate the damage caused by an initial, low heat release rate fuel and the influence on this initial damage when a secondary fuel with a substantially higher heat release rate and total energy output becomes involved within a compartment fire. NFPA 921 cautions investigators regarding this in the following:

> 17.4.1.3.1 The size, location, and heat release rate of a fuel package may have as much effect on the extent of damage as the length of time the fuel package was burning. An area of *extensive damage may simply mean that there was a significant fuel package at that location. The investigator should consider whether the fire at such a location might have spread there from another location where the fuel load was smaller* (emphasis added) [2].

NFPA 921 further cautions the investigator that when analyzing fire patterns, it is imperative that the investigator determines the sequence of pattern generation in determining the area of origin. Thus, the primary question of the obscuration of the initial damage must be taken into consideration when using fire patterns to arrive at an area of origin. However, this research question has not been sufficiently addressed in the current literature. In order to provide some guidance in this area, a total of fourteen full-scale compartment fire tests have been completed with the fire origin located at a lower heat release rate fuel (i.e. nightstand, end table) adjacent to a higher heat release rate fuel (i.e. sofa, mattress). For comparison, a total of ten full-scale compartment fire tests have been completed with the origin located within the higher heat release rate fuel. All of the tests completed were allowed to transition through flashover and burn in the post-flashover regime for a limited duration. It was the focus of this research to obtain a baseline for the post-flashover patterns with the intent of studying longer duration fires in future testing.

METHODOLOGY

In order to isolate the heat release rate variable, a testing series was conducted in which full-scale tests were performed in two identically constructed rooms. These tests were conducted on the same day, in duplicate test cells, with the same furniture [3, 4]. Environmental factors, such as ventilation, were controlled as much as possible. Previous full-scale fire tests have been published regarding the analysis of the general reproducibility, usage, reliability, and persistence of fire patterns for fire investigation [7, 9-12, 23].

A total of twenty-four full-scale compartment fire tests have been conducted as part of this study. Ten full-scale compartment fire tests were conducted with the origin located within the higher heat release rate fuel (e.g. sofa or mattress) to evaluate reproducibility of damage location and magnitude [9-12]. Fourteen full-scale compartment fire tests were conducted with the origin located within the lower heat release rate fuel (e.g. nightstand or end table) adjacent to the higher heat release rate fuel. Twelve tests were furnished as residential bedrooms and twelve tests were furnished as residential living rooms. The contents have remained the same throughout the twenty-four tests, however, the location of the origin, the ventilation, and the layout of the room has varied throughout the series of tests.

Test Facility

The burn facility located at Eastern Kentucky University was used for all tests. The burn building consists of duplicate cells. Each burn cell was framed with standard 2”x4” wall studs and 2”x6” ceiling joists (Figure 1). All interior wall surfaces were lined with ½” gypsum wallboard and were finished with sheetrock mud and tape as would be expected in a standard residential home. All of the furniture used throughout these tests was purchased new for each series in an attempt to maintain consistency in fuel items.

Rooms with features resembling typical residential bedrooms and living rooms were constructed within the “test burn building.” The identical test 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 bedroom 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 bedroom 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 bedroom 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 (6’10”). The overall dimensions of the window frames were approximately 1.06m (3’6”) wide and 0.91m (3’0”) high, with the sill 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 glass windows. Figure 1 contains a graphical representation of the test rooms and the layouts used within this study.

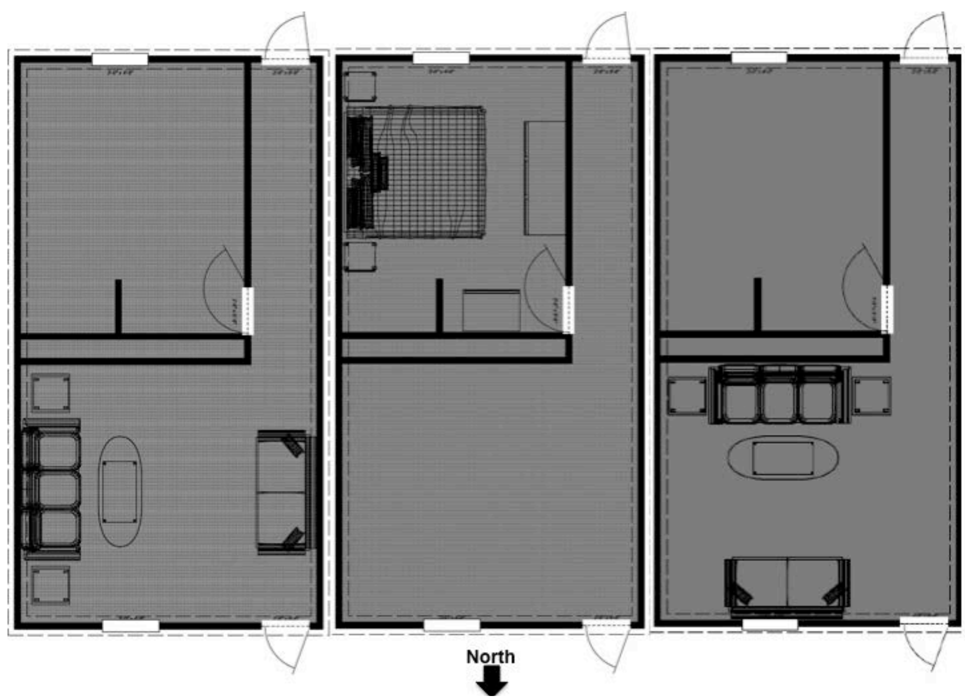

Figure 1. Test Facility Living Room Layout 1 (left); Test Facility Bedroom Layout (center); Test Facility Living Room Layout 2

Experimental Design

Since this experimental series has seen over 20 full-scale tests performed, this paper will report on two representative tests that were furnished as residential living rooms (Living Room Layout 2-Figure 1). The living room as well as the hallway had wall-to-wall carpeting on the floor. Each living room was furnished with a polyurethane foam sofa and loveseat, two end tables, and a coffee table. The sofa was located along the south wall with end tables on both sides and a coffee table centered in front. The loveseat was located along the north wall. The north doorway to the exterior of the building was opened 11-inches for the duration of the test. A single pane glass window was installed in the north wall, which provided a source of ventilation upon failure during the test.

The first test was conducted on March 17, 2010, with a polyurethane foam sofa (large heat release rate fuel) being the first fuel ignited located along the south wall. The second test was conducted on April 26, 2011, with the first fuel ignited being the end table located on the right side (west) of the sofa along the south wall (Figure 2).

Figure 2. Different Origins (left) test 1; (right) test 2

Environmental conditions and additional test parameters are documented in Table 1 for the two tests reported here, including the location and size of ventilation openings, failure of windows, timing of events, and general descriptions for each test. The following provides a general list of standard testing methodology and equipment utilized throughout the test for documentation.

Table 1 Experimental Test Conditions and Times

Test	Temp (^oF)/ Humidity	Wind Speed (mph)/Dir	Ignition Location & Method	Ventilation	Window fails (min:sec)	Extinguished (min:sec)
1	52 / 63%	3.5 / SSE	Center sofa w/ gauze & 5ml of gas	Door partially open (11”)	4:10	5:51
2	66 / 68%	11.5 / SSW	9” heptane pool fire under right end table	Door partially open (11”)	9:30	13:20

Instrumentation

The rooms were instrumented for the measurement of temperature with thermocouple (TC) arrays strung vertically between the ceiling and the floor (a.k.a. thermocouple trees) located in the center of the living room. Each experiment contained 8 TC leads in the tree spaced one foot apart, starting from the ceiling down. Each test cell had a single additional thermocouple, not associated with the thermocouple tree, positioned on the ceiling directly above the point of ignition. All thermocouple data was logged and stored electronically at regular intervals of 3 seconds.

Additionally, each test had a heat flux transducer placed on the floor. The radiant heat flux at the floor of the living room was measured with a water cooled, Schmidt-Boelter type heat flux transducer. The transducer was equipped with a Zinc Selenide (ZnSe) window to exclude convective heat flux. The view of the transducer, with the ZnSe window installed, was approximately 150^o. The transducers were installed near the west end table on the floor in each test cell.

In addition to the above instrumentation, digital 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. Finally, a thermal imaging camera was utilized to record each experiment.

Initial Fuel

The sofa in test one was ignited by the application of a propane torch to a small plastic bag containing a 4”x4” piece of cotton gauze doused with approximately 5 ml gasoline. The polyurethane sofa was estimated to have a peak heat release rate between 2-3 MW.

A 9-inch diameter heptane pool fire was chosen to represent the initial, low heat release rate fuel for test two. A small pool fire was selected for this experimental series due to their extensive use in fire research and the data provided by these studies that enable the heat release rate and duration of burning to be calculated [20].

$$\dot{Q} = \dot{m}'' \Delta H_{c,eff} A_f \left(1 - e^{-k\beta D}\right) \quad (1)$$

Where $\dot{Q}$ is the heat release rate (kW). The mass loss rate for heptane was estimated to be (C_7H_{16}) $\dot{m}'' = 0.101 \frac{kg}{m^2 - sec}$; the heat of combustion as $\Delta H_{c,eff} = 44{,}600 \frac{kJ}{kg}$; the area, A_f=0.04 m^2; and the empirical constant as $k\beta = 1.1\ m^{-1}$ [30]. This resulted in a calculated 48 kW peak heat release rate fire with an approximate burning duration of 4 minutes.

Fire Scene Analysis Techniques

Following each of the fire experiments, the conditions of the wall and ceiling linings, room contents, and the building components were analyzed. Each experiment was documented by photography, written notes, and diagrams. Each scene was thoroughly processed using generally recognized and accepted techniques and methods as outlined in NFPA 921-Guide for Fire and Explosion Investigations [2].

Three specialized scene processing techniques were employed during the post-fire analysis of each experiment; a depth of calcination diagram, a depth of char survey, and a heat and flame vector analysis diagram. The methodology for each technique and the resulting diagrams were prepared in accordance with NFPA 921 [2].

The process to evaluate post fire burn damage begins by identifying the visible and measurable damage to each wall and ceiling surface. Schroeder performed research on the use of gypsum wallboard for his dissertation and found that it can be considered a reliable source of information of heat exposure [24]. Thus, investigators can assess gypsum wallboard post-fire by both visual and measurable means.

The contents within the compartment were also evaluated using two scales (1) the damage to each item was compared to the damage to the other items within the compartment, and (2) each surface of the item was compared to other surfaces on that item. For example, the end tables were first compared to each other (left versus right), and then each surface for the end table is compared to each other (i.e. the top surface is compared to the sides and the underside). Damage to objects was quantified by visual inspection (qualitative) and by depth of char measurements (semi-quantitative).

Visible Fire Effects to Wall Surfaces and Contents

The wall and ceiling lining material used in the test was ½-inch (12.7mm) gypsum wallboard covered with a single coat of latex paint. Gypsum wallboard is a common interior structural lining material consisting of a core of gypsum (calcium sulfate dehydrate) sandwiched between two paper facers [27]. There are several effects that may occur to gypsum wallboard when exposed to heat and fire conditions, including: color changes, soot deposition, charring of craft paper, consumption of craft paper, and clean burn [2]. Determining which effect or effects reflect varying degrees of damage is the key to successfully assessing damage. Two methods are used to visibly identify damage on gypsum wallboard (1) by cross-sections, (2) surface identification.

Most of the published research has focused on examining cross-sections of the wallboard, visibly determining the depth of calcination based on different bands of color within the cross-section [25-28]. However, research by Kennedy revealed the cross-sectioning method had inherent procedural drawbacks to the practical fire investigation [25]. All of the studies consider measuring the depth of calcination by taking depth caliber and probing it into the wall, a more effective method for use in the field. Consequently, the cross-sectioning of wallboard was not utilized for this experiment series.

Typically investigators look at the face of the wallboard and make a visible estimation of the degree of damage. The visible appearance of wallboard has been utilized in all published fire pattern studies available, even though only a few studies exist that focus on the baseline characteristic of the varying degree of heating and resulting degree of damage [6, 9-10]. Therefore, no systematic procedure exists to base a scaling factor for the degree of damage. NFPA 921 states that gypsum wallboard has a predictable response to heat and provides guidance regarding the response of gypsum wallboard to varying levels of heat in Sections 6.2.12.1.1 and 6.2.12.1.2 [2]. The varying degree of damage to gypsum board is discussed in NFPA 921 and is consistent with information published in the literature, and therefore, indications of visual damage were used throughout this study as an indicator of heat exposure [6, 9-10]. As an attempt at standardization, the level of damage to gypsum board based on varying amounts of heat exposure have been reproduced and adapted here as Table 2.

Table 2 Visible Damage Scale

↓ Increasing Exposure to Heat	Damage Description	Visible Effect
	No Damage	No soot deposit; no effect
	Minor Damage	Soot deposition; Discoloration
	Moderate Damage	Paper surface charred; Paint consumed
	Heavy Damage	Paper consumed; Exposed gypsum changes color
	Severe Damage	White/bluish color = Clean Burn
	Total damage	Total destruction: crumbly, less dense solid=loss of mass

In addition to the gypsum wallboard analysis as a damage indicator, all of the contents of the test cells were visually inspected and a description of the damage noted for the analysis. First, a comparative analysis for each exterior surface of a content item is discussed, followed by a comparison between contents. As the contents are constructed of different materials (i.e. wood, polyurethane foam), the visual assessment of the damage is based on the type and degree of damage as interpreted by the authors (as it would be if done in the field).

Depth of Calcination

To standardize the depth of calcination evaluation, each wall surface was first divided into a one-foot by one-foot grid. Snapping chalk lines on the wall surface at one-foot intervals enable the creation of the grid. At each intersection of the grid lines, the extent of measurable damage was recorded. A graphic representation of the grid layout can be seen in Figure 3.

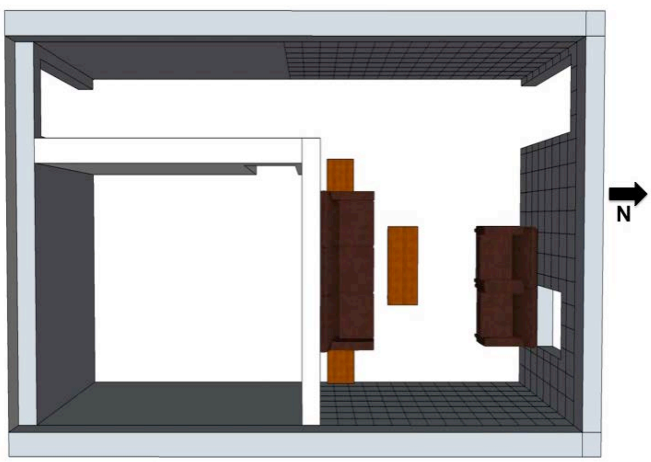

Figure 3. Graphical representation of the 1ft x 1 ft grid for each wall

Depth of calcination measurements were taken and recorded utilizing a depth gauge on the one-foot by one-foot grid. This process is sometimes referred to as a probe survey. “Probe survey” methods consist of using a calibrated probe caliper-like device to determine the depth of heat exposure or dehydration to the gypsum wallboard. The instrument is inserted perpendicularly into the surface of the heat-treated material, and by feeling the difference in resistance between the effected and non-effected cross-sections, the relative amount of heat treatment is noted.

Schroeder’s findings on the use of gypsum wallboard encouraged other researchers to examine whether practical methods existed for determining the depth of calcination [24]. Kennedy evaluated a variety of probing methods and the use of the depth of calcination method as it related to determining an area of origin [25]. He reported that the depth of calcination method in conjunction with fire pattern analysis produced accurate and reproducible results [25].

Mann and Putaansuu performed a series of standardized tests with gypsum wallboard, a variety of heat source intensities (i.e. cone calorimeter, propane), and various durations [26]. Their findings further confirm that the probe survey method "can yield results that find the depth of total dehydration (the anhydrous layer)" by "using simple tools and consistent pressure" [26].

Based on the methodologies recommended by previous studies and the findings of Kennedy and Mann and Putaansuu, a constant probe pressure was adhered to in this study. However, no uncertainty analysis was performed. The results are presented in a table format representing the elevation view of each wall. The relative locations of the contents along each wall have also been labeled. For illustration purposes only, the depth measurements have been divided into 5 different colors based on actual depth measurements (Table 3).

Table 3 Damage scale based on actual depth measurements

11-13 mm
8-10 mm
5-7 mm
2-4 mm
0-1 mm

Heat and Flame Vector Analysis

To determine if a fire pattern exists, the investigator analyzes the collected data and looks for trends. A technique, termed *heat and flame vector analysis*, has been developed for the simple documentation of fire patterns on a diagram. The heat and flame vector analysis technique is discussed at length in NFPA 921 [2]. This paper adopts this process of identifying the fire pattern on a diagram as an arrow.

The arrows or vectors, as NFPA 921 terms them, are only intended here to record directional damage and do not necessarily illustrate magnitude for this paper. For purposes of this discussion, the line portion of the arrow (-) illustrates the greater damage and the tip of the arrow (>) illustrates the lesser damage (arrows will be pointing in the direction of lesser damage). Each arrow will correspond to a legend that identifies what fire effect or group of fire effects served as the evidence to indicate the designated direction of damage. A heat and flame vector (arrow) was drawn on the respective diagram for each pattern in each experiment to represent the direction of movement (fire spread).

Area of Origin Determination

The heat and flame vector analysis can be used in combination with other techniques to identify the area of origin by recording the trends with the collected data that exist within the compartment. It is then the investigator's responsibility to accurately interpret the data and assign weight to the damage as it relates to the area of origin analysis [29]. Arrival at a hypothetical area of origin requires the analyst to test the hypothesis by asking several questions [29]: (1) is an ignition source present or not present? (2) Was a fuel present or not? (3) Is the actual damage observed consistent with expected damage based on first fuel ignited and fire growth? (4) Is the ignition source competent compared to the first fuel ignited? (5) Can the first fuel ignited result in the fire spread scenario that resulted in the damage observed? (6) Is there more than one hypothetical areas of origin?

GENERAL TEST RESULTS

Test 1 Results

Test one was conducted on March 17, 2010. This test lasted for approximately six minutes with the window failing around 250 seconds, flashover occurring around 310 seconds, and extinguishment at 370 seconds. Flashover was determined visually by the ignition of the carpet inside the doorway and by the presence of flaming combustion exterior of the compartment through the window and doorway. This timing was confirmed by two technical indicators for flashover, an upper layer temperature of 600°C and a heat flux of 20 kW/m^2 at the floor level (Figures 4-5).

Temperatures were in excess of 300°C for approximately 200 seconds. Heat flux values in excess of 55 kW/m^2 were found to exist at the floor level.

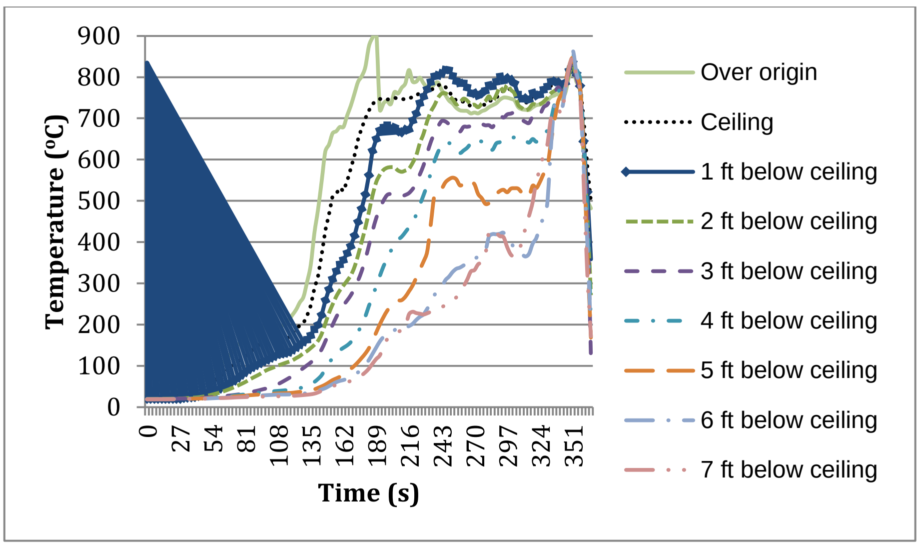

Figure 4. Test 1 Temperature Measurements – Sofa Origin

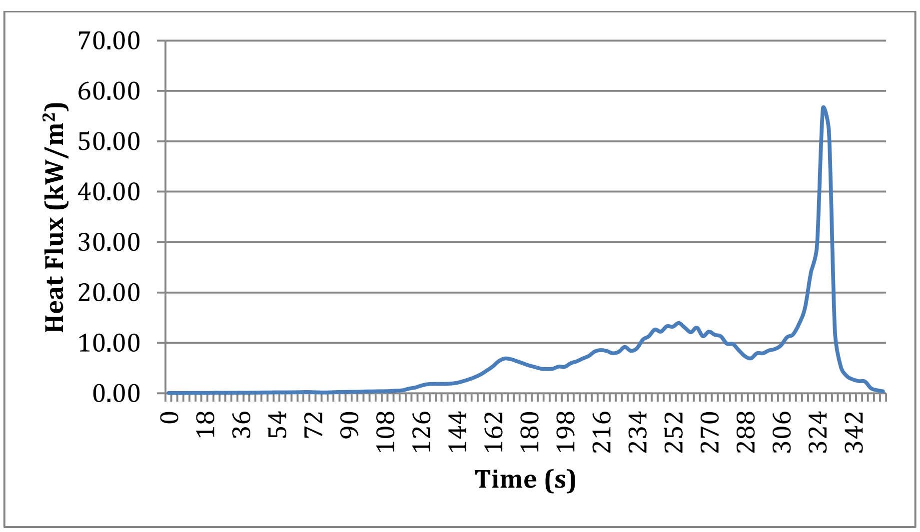

Figure 5. Test 1 Heat Flux Data at Floor Level – Sofa Origin

Test 1 Visible Damage Results

The north wall exhibits heavy to severe damage across its entire surface from the ceiling to approximately a foot off the floor. There is a protected area located behind the loveseat. The entire width and height of drywall above the seam is heavily damaged with the paper consumed and the gypsum wallboard changing to a black or dark grey color. The greatest visible damage is the severe damage that extends from the floor to the drywall seam between the doorway and the loveseat (Figure 6).

The vertical cushion for the backrest of the loveseat is completely consumed and the finishing fabric along the horizontal cushion has been consumed, however, the horizontal padding is still present. The loveseat has relatively uniform damage extending from the top of the backrest down to the horizontal cushions. The kickboard of the loveseat is uniformly charred both in width and height. The back face of the sofa was protected and displays no thermal effects. The left armrest of the sofa, nearest the door, has char greater and lower in elevation than the right armrest.

Figure 6. North Wall - Test 1 (Sofa Origin)

The east wall has moderate damage along the upper portions of the entire wall, minor damage below the drywall seam, and heavy damage in the south corner nearest the sofa (Figure 7).

Figure 7. East Wall - Test 1 (Sofa Origin)

The south wall has the greatest degree of visible damage comparative to all other walls (Figure 8). Damage in the center of the wall extends from floor to ceiling. Increasing lines of demarcation move outward from the center of the wall towards the hallway and east wall. The greatest area of clean burn in the compartment is witnessed in the center of the wall extending from floor to ceiling. Protected areas are witnessed behind each of the end tables.

Figure 8. South Wall - Test 1 (Sofa Origin)

The sofa that was located along the south wall had near complete consumption of its cushions and complete consumption of its finishing fabric. The majority of the wood frame remains intact, except for the center-left vertical backrest support. The left end (east) of the sofa exhibits complete loss of padding, while the right end (west) of the sofa still has a small amount of padding remaining. The interior sides of both armrests have significantly greater charring versus the exterior sides. The kickboard has greater charring and mass loss in the center and lesser damage towards each end. The sofa was damaged considerably more than the loveseat and the other contents within the compartment (Figure 9).

The laminate wood veneer coating covering the top of the coffee table has greater loss of mass on the side nearest the sofa. The lateral support facing the sofa, visibly appears to have greater and deeper charring (i.e. deeper and more cracks in the wood) than the other faces. The legs closest to the sofa visibly appear to have greater and deeper charring near the side of the sofa, while the legs opposite the sofa exhibit lesser damage. The interior of the legs and the underside of the table have received only slight thermal damage (Figure 9).

The right end table (west of sofa) has greater damage on the left face, nearest the sofa. The veneer has begun to peel off and mass has been lost. The front face of this end table exhibits lesser damage to its veneer than the left face. The veneer on the back and right side of the end table exhibit no thermal damage (Figure 9).

The left end table (east of sofa) has greater damage on the right side nearest the sofa. The right face of the table is the only side that exhibits any damage to the veneer (Figure 9).

Figure 9. Sofa and Tables - Test 1 (Sofa Origin)

The south end of the west wall has moderate to heavy damage with an increasing line of demarcation as one moves down the hallway (Figure 10). The north end of the west wall (nearest the door) has heavy to severe damage extending from floor to ceiling. In addition, there is an area of clean burn located off the floor between 3 and 5 feet that extends 5 feet into the compartment from the doorway.

Figure 10. West Wall - Test 1 (Sofa Origin)

Test 1 Depth of Calcination Results

The greatest depth of calcination along the north wall was located next to the doorway (Figure 11). The remainder of the wall appears to have similar depth measurements, with slightly greater depths also around the window.

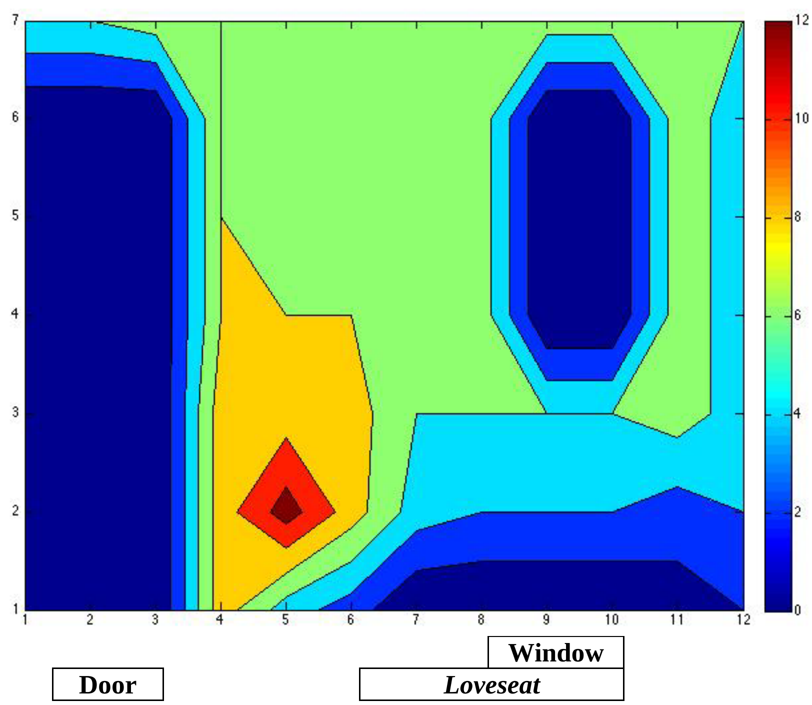

Figure 11. North Wall - Test 1 (Sofa Origin)

The greatest depth of calcination along the east wall was located in the south corner above the end table and sofa (Figure 12). This is most likely due to the ceiling jet and collection of upper layer gases in this corner from the fire plume on the sofa.

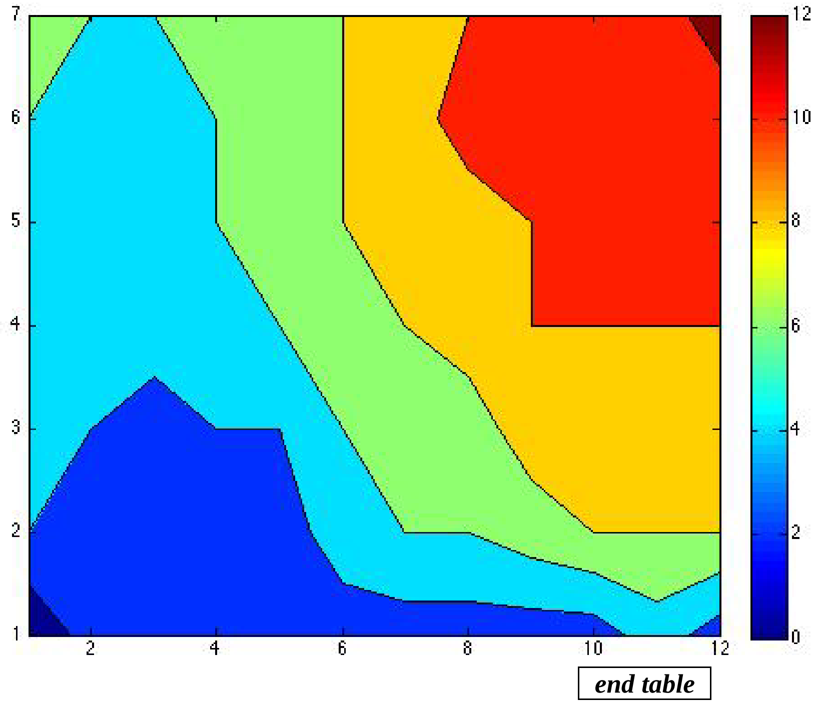

Figure 12. East Wall - Test 1 (Sofa Origin)

The south wall had the deepest measurements and the greatest area of calcined material in the compartment (Figure 13). The greatest depth measurements were found in the center of the wall, with several measurements going completely through the wallboard directly behind the center of the sofa. The depth measurements lessened towards the hallway and east walls. The greater depth measurements were expected along this wall due to sofa being the first fuel ignited and largest fuel in the compartment.

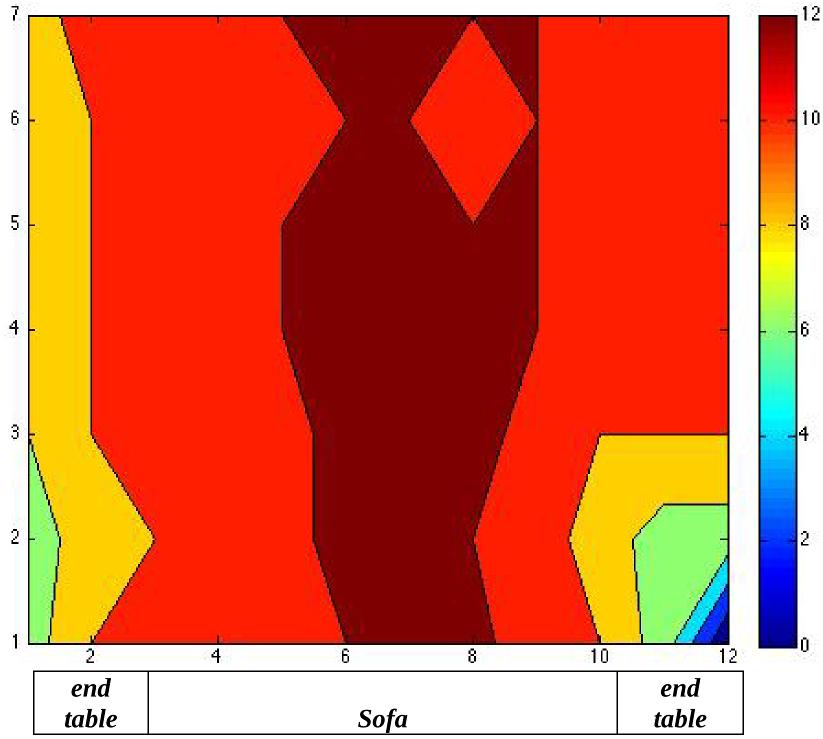

Figure 13. South Wall - Test 1 (Sofa Origin)

The greater depth of calcination measurements along the west wall was located above the drywall seam. The depth of calcination along this wall was lesser in comparison to the other walls (Figure 14). The significant visible damage noted in Figure 10 was not illustrated to the same extent in the depth of calcination measurements (Figure 14). This possibly indicates that the surface of the wallboard was influenced by the ventilation-controlled combustion at this location, but the total heat transfer into the wall was significantly less due to a shorter duration and/or less intense heat flux. Resulting in a pronounced visible damage, but not reflected to the same extent in the measurable damage.

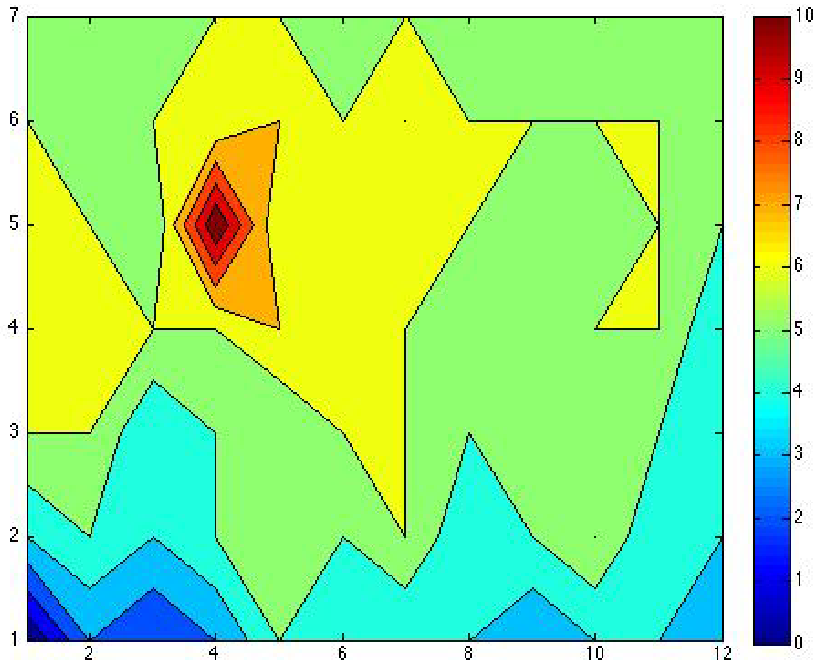

Figure 14. West Wall - Test 1 (Sofa Origin)

Test 1 Heat and Flame Vector Analysis

The heat and flame vector analysis diagram indicates two areas within the compartment where damage emanates (Figure 15, Table 4). The majority of the damage within the compartment can be traced back to the center of the sofa. However, there is damage that appears to emanate from the location of the door opening.

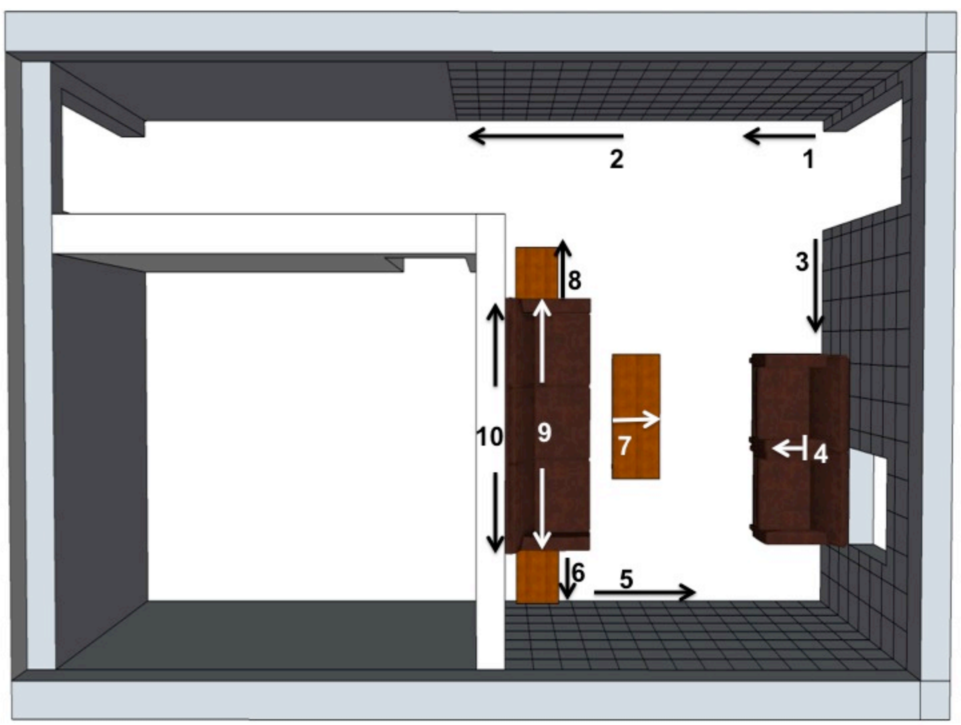

Figure 15. Heat and Flame Vector Analysis Diagram - Test 1 (Sofa Origin)

Table 4 Heat and Flame Vector Analysis Legend – Test 1 (Sofa Origin)

Vector	Material	Effect	Fire Patterns Analysis
1	Gypsum wallboard	Clean burn	Clean burn extending from doorway 5' into compartment. Indicating intensity near the doorway.
2	Gypsum wallboard	Color change	Increasing line of demarcation moving down hallway. Indicating fire travel from living room down the hallway.
3	Gypsum wallboard	Clean burn	Clean burn extending from doorway to loveseat. Indicating intensity near doorway.
4	PU foam	Loss of mass	Backrest cushion completely consumed, horizontal cushion still present. Near uniform heat from top down, indicating a hot gas layer generated pattern.
5	Gypsum wallboard	Depth of calcination	Deeper calcination measurements in S corner of east wall. Indicating fire travel from S end of room towards N.
6	Wood	Char; depth of char	Greater visible and measurable char near sofa. Indicating fire travel from sofa.
7	Wood	Char; depth of char	Greater visible and measurable char near sofa. Indicating fire travel from sofa.
8	Wood	Char; depth of char	Greater visible and measurable char near sofa. Indicating fire travel from sofa.
9	PU foam / wood	Loss of mass; char	Greater char and loss of mass in center of sofa. Indicating fire travel from sofa.
10	Gypsum wallboard	Clean burn; depth of calcination	Greatest area of clean burn and depth of calcination above and behind center of sofa. Indicating fire travel from sofa.

Test 1 Area of Origin Determination

Based on the heat and flame vector analysis, there are two hypothetical areas of origin that must be evaluated (1) the center of the sofa, and (2) the location around the doorway. As this compartment was ventilation-controlled for some time, the damage around the open ventilation source is expected and should not warrant a significant weighting in the analysis of the area of origin [8]. In addition, an origin determination should also evaluate the first fuel ignited and the presence of a competent ignition source within those hypothetical areas of origin. At the doorway location, there is neither a first fuel nor a competent ignition source, further decreasing the weight of this hypothetical area of origin.

The second area of origin hypothesis is much more plausible and supported by the compartment fire dynamics. The complete loss of mass to the sofa, the directional damage to the surrounding tables emanating from the sofa, the greatest visible and measurable damage located along the south wall directly behind the sofa, and most importantly the sofa being a plausible fire scenario that was capable to cause the resulting damage and fire progression is enough evidence to lead the investigator to the sofa as the first fuel ignited.

TEST 2 RESULTS

Test two was conducted on April 26, 2011. This test lasted for approximately 13 minutes and 20 seconds with the window failing around 570 seconds. The time to flashover is somewhat debatable due to the mixture of indicators witnessed. The technical indicators for flashover including a heat flux of 20 kW/m^2, temperatures in the upper layer nearing 600 ^{o}C, and persistent flames exiting the door opening were witnessed at 380 seconds, but the fire became ventilation-controlled and began to decay shortly after this. Once the window failed, the fire again began to grow, with extinguishment taking place at approximately 800 seconds. Flashover was determined visually by the ignition of the carpet inside the doorway and by the presence of flaming combustion exterior of the compartment through the window and doorway. This timing was confirmed by two technical indicators for flashover, an upper layer temperature of 600^{o}C and a heat flux of 20 kW/m^2 at the floor level (Figures 16-17).

Temperatures were in excess of 300^{o}C for approximately 500 seconds. Heat flux values in excess of 70 kW/m^2 were found to exist at the floor level. These readings may be higher due to the proximity of the heat flux transducer to the initial fuel items.

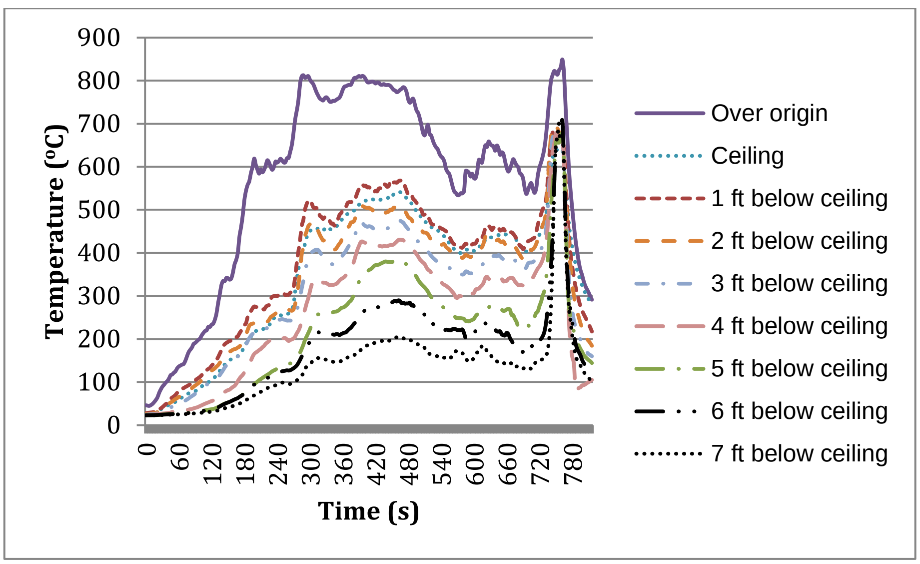

Figure 16. Test 2 Temperature Measurements – End Table Origin

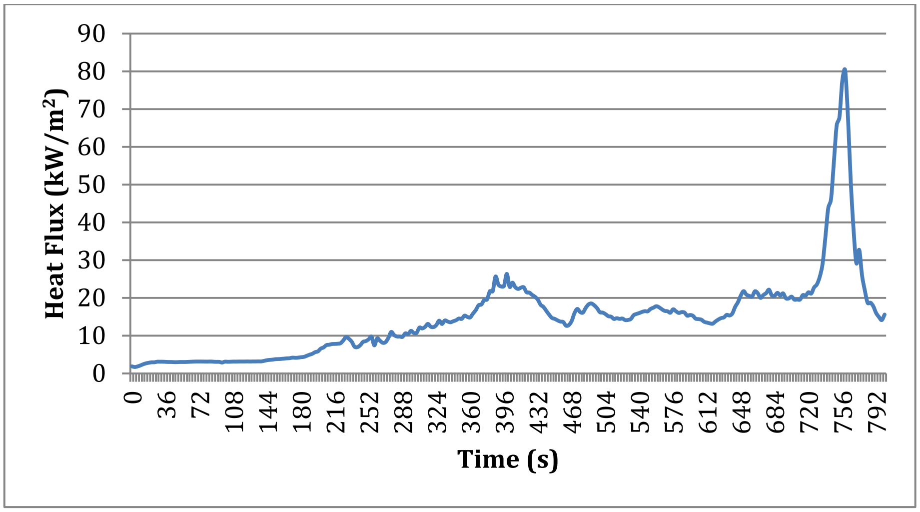

Figure 17. Test 2 Heat Flux Data at Floor Level – End Table Origin

Test 2 Visible Damage Results

The north wall has a uniform line of demarcation approximately three feet off the floor that separates clean burning to the upper portions of the wall and paper consumption in the lower portions (Figure 18).

Identical to test 1, the vertical cushion for the backrest of the loveseat is completely consumed and the finishing fabric along the horizontal cushion has been consumed, however, the horizontal padding is still present. The loveseat has relatively uniform damage extending from the top of the backrest down to the horizontal cushions. The kickboard of the loveseat is uniformly charred both in width and height. The back face of the sofa was protected and displays no thermal effects. The left side of the sofa, the side near the door, has char greater and lower in elevation than the right side.


Figure 18. North Wall - Test 2 (End Table Origin)

The east wall has a roughly uniform line of demarcation separating the upper portions of the wall that have significant clean burning from the lower portions of the wall that have charred craft paper only (Figure 19). The line of demarcation is lowest in the south corner, near the sofa.

Figure 19. East Wall - Test 2

The south wall has the most severe damage and greatest area of clean burning within the compartment (Figure 20). The clean burn damage extends from floor to ceiling starting from the west end of the wall to approximately the left armrest of the sofa. An increasing line of demarcation extends from the left end of the sofa to the east wall, with clean burn damage above this line and a protected area behind the left end table (east).

Figure 20. South Wall - Test 2 (End Table Origin)

The sofa that was located along the south wall had complete consumption of its cushions, finishing fabric, and wooden backrest support. The right arm of the sofa has also lost the majority of its mass and structural integrity. The left arm of the sofa has significant char on the interior face, while the exterior face has only slight char. The kickboard has progressively greater mass loss and charring on the right side versus the left. The sofa had considerably greater damage than the loveseat (Figure 21).

The lateral support of the coffee table closest to the sofa visibly appears to have greater and deeper charring (i.e. deeper and more cracks in the wood) than the other surfaces. The legs closest to the sofa visibly appear to have greater and deeper charring, while the legs opposite the sofa exhibit lesser damage. The leg closest to the right side of the sofa has the greatest damage. The interior of the legs and the underside of the table have received only slight thermal damage (Figure 21).

The right end table (west of sofa) has the greatest charring and loss of mass compared to any of the other tables. The top of the table has lost most of its mass. The left lateral support (left face) has been completely consumed. The front and back faces have significant mass loss and deep charring. The right face has only slight charring. The left side legs, both their interior and exterior faces, have deep charring and significant mass loss. The right side legs have deep charring on the interior faces, but limited thermal damage to their exterior faces. The right end table had considerably greater damage compared to the other tables within the compartment (Figure 21).

The left end table (east of sofa) exhibits greater damage on the right side nearest the sofa. The right face of the table is the only side that exhibits any thermal damage (Figure 21).

Figure 21. Sofa and Tables - Test 2 (End Table Origin)

The upper half of the west wall has clean burn damage (Figure 22). The lowest area of clean burn starts approximately one foot below the drywall seam and extends from the doorway to approximately 9 feet into the compartment. Near the center of the wall is the lowest area of damage that extends from floor to ceiling. On either side of this area are increasing lines of demarcation moving towards the door and down the hallway.

Figure 22. West Wall - Test 2 (End Table Origin)

Test 2 Depth of Calcination Results

The greatest depth of calcination along the north wall was located around the doorway and the window (Figure 23).

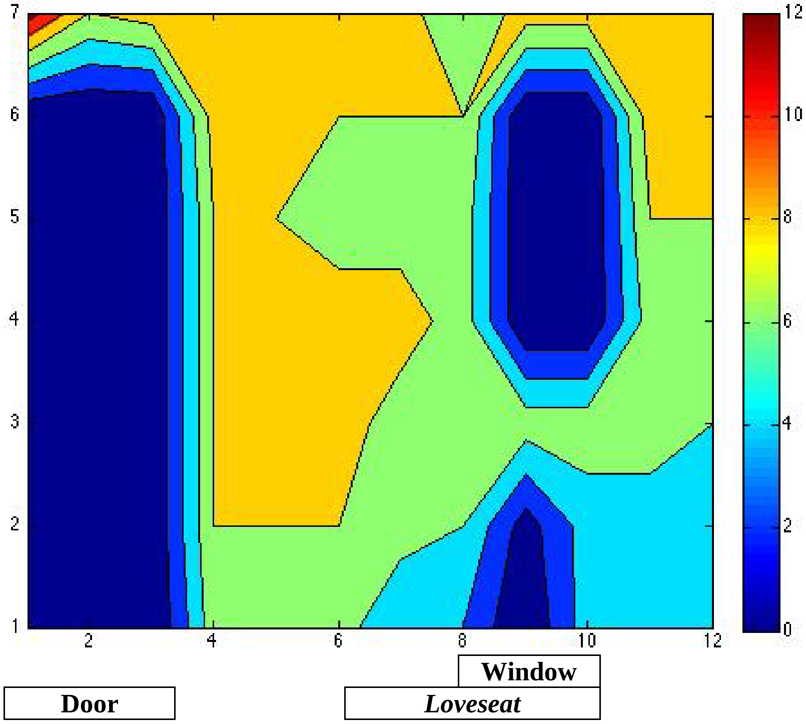

Figure 23. North Wall - Test 2 (End Table Origin)

The greatest depth of calcination along the east wall is located in the south corner above the the end table and sofa (Figure 24). This was most likely caused by the ceiling jet and upper layer gases forming in this corner.

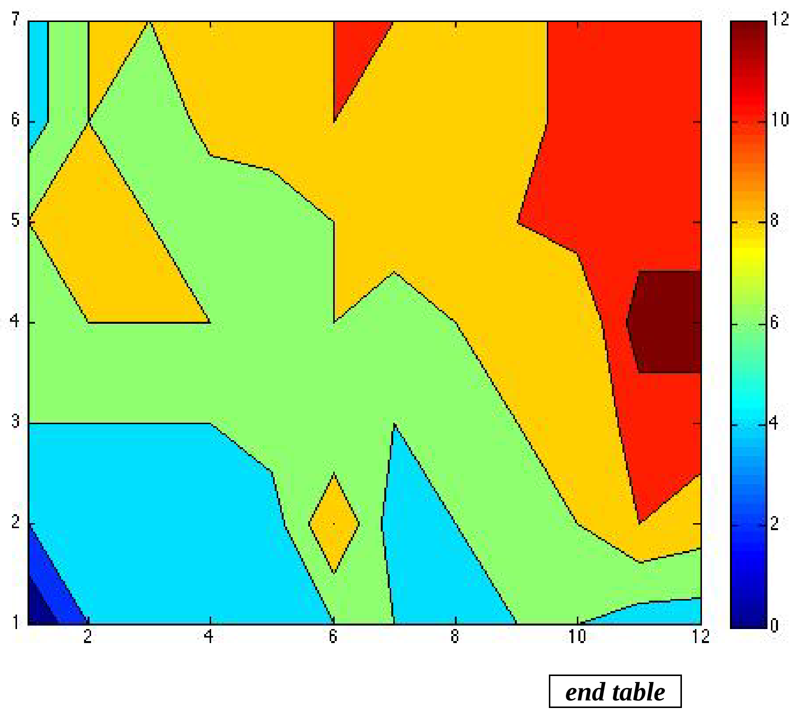

Figure 24. East Wall - Test 2 (End Table Origin)

The greatest depth measurements and the greatest area of calcined wallboard was located on the south wall (Figure 25). The right side and center of the wall had the greatest depth measurements, with several measurements going completely through the wallboard directly behind the right end table and right side of the sofa. The measurements were less towards the east wall.

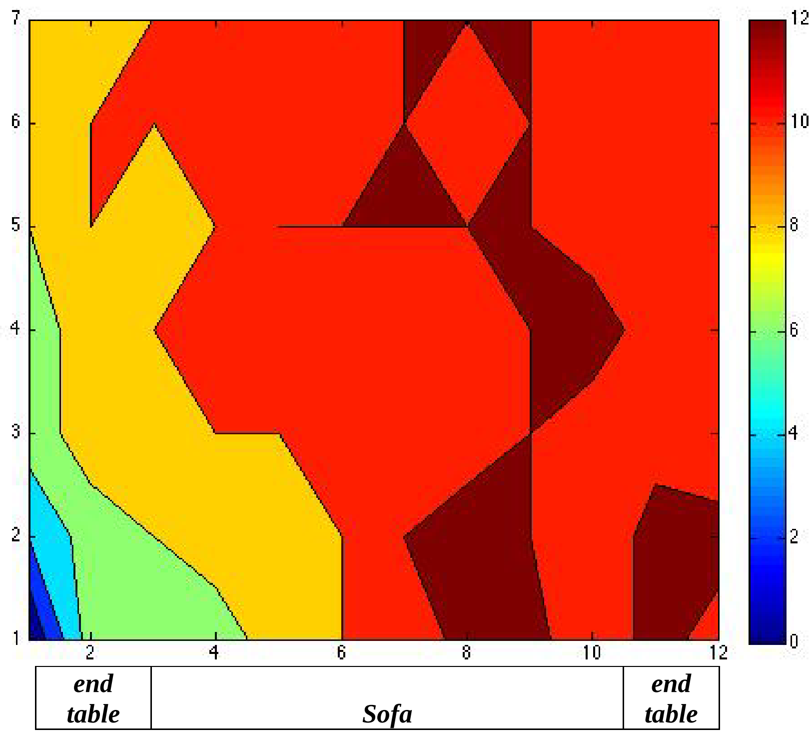

Figure 25. South Wall - Test 2 (End Table Origin)

The greatest depth of calcination measurements along the west wall were found above the drywall seam nearest the doorway (Figure 26).

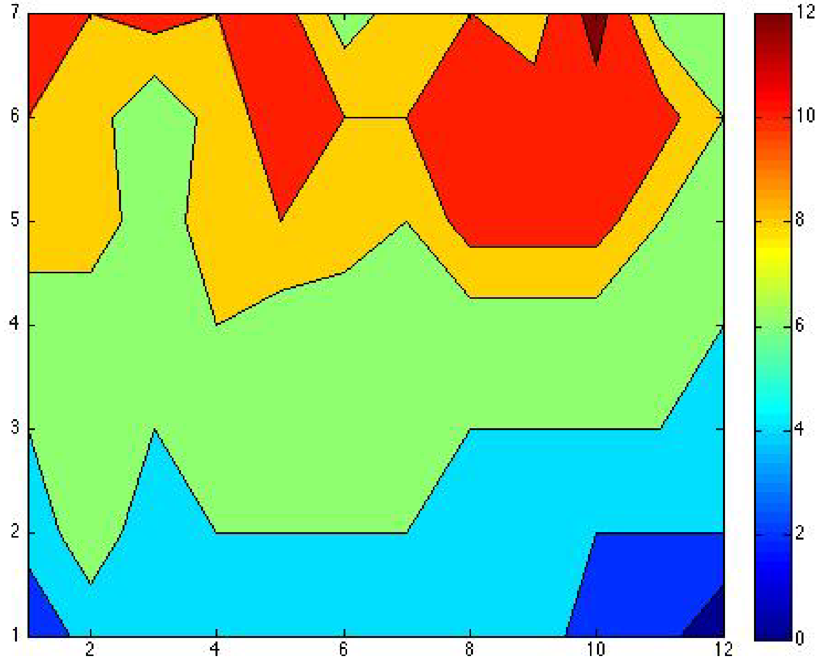

Figure 26. West Wall - Test 2 (End Table Origin)

Fire Patterns Analysis (Heat and Flame Vector Analysis)

The heat and flame vector analysis diagram indicates three areas within the compartment where damage emanates (Figure 27, Table 5). The majority of the damage within the compartment can be traced back to the right side of the sofa and/or the right end table. However, similar to test 1, there is damage that appears to emanate from the location of the door opening.

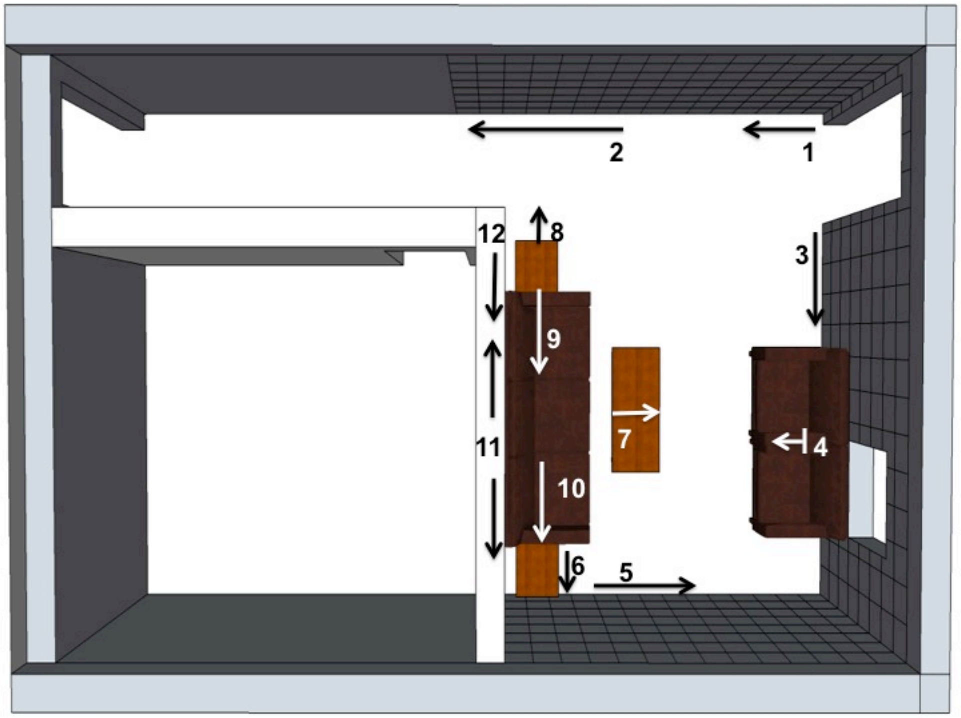

Figure 27. Heat and Flame Vector Analysis Diagram - Test 2 (End Table Origin)

Table 5 Heat and Flame Vector Analysis Legend – Test 2 (End Table Origin)

Vector	Material	Effect	Fire Patterns Analysis
1	Gypsum wallboard	Clean burn	Clean burn extending from doorway 5’ into compartment. Indicating intensity near the doorway.
2	Gypsum wallboard	Color change	Increasing line of demarcation moving down hallway. Indicating fire travel from the living room into the hallway.
3	Gypsum wallboard	Clean burn	Clean burn extending from doorway to loveseat. Indicating intensity near the doorway.
4	PU foam	Loss of mass	Backrest cushion completely consumed, horizontal cushion still present. Near uniform heating from top down. Indicating a hot gas layer generated pattern.
5	Gypsum wallboard	Depth of calcination	Deeper calcination measurements in s corner of east wall; increasing line of demarcation towards n wall. Indicating fire travel from south end of room to north.
6	Wood	Char; depth of char	Greater visible and measurable char near sofa. Indicating fire travel from sofa.
7	Wood	Char; depth of char	Greater visible and measurable char near sofa. Indicating fire travel from sofa.
8	Wood	Char; Loss of mass	Loss of mass near sofa. Indicating fire travel from end table.
9	PU foam / wood	Loss of mass; char	Near complete loss of mass to right armrest; greater loss of mass and char along right side of kickboard. Indicating fire travel from end table.
10	PU foam / wood	Loss of mass; char	Interior face of left armrest significant charring versus slight char on exterior face. Indicating fire travel from

			rt side of sofa.
11	Gypsum wallboard	Depth of calcination	Largest area of clean burn; deep calcination behind right side of sofa and lesser towards hallway and east wall. Fire travel from rt side of sofa.
12	Gypsum wallboard	Depth of calcination	Great area of clean burn; deep calcination measurements behind end table. Indicating fire travel from end table.

Area of Origin Determination – Test 2

Based on the heat and flame vector analysis, there are three hypothetical areas of origin that must be evaluated (1) the right side of the sofa, (2) the right end table, and (3) the location around the doorway. As discussed in the previous test, this compartment was ventilation-controlled for some time. Therefore, the damage around the open ventilation source is expected and should not warrant a significant weighting in the analysis of the area of origin [8].

The sofa has complete loss of mass. There is more loss of mass to the right side of the couch compared to the left side, including greater char and mass loss to the kickboard and the complete loss of the mass to the right armrest. The left end table has moderate char along those surfaces facing the sofa, but nothing compared to the damage and loss of mass to the right end table. The depth of char from the coffee table indicates deeper char along the surface facing the sofa with the greatest depths near the right end table. The exterior side of the sofa's left armrest received very minor charring compared to the interior side facing the polyurethane foam. The right armrest of the sofa has near complete loss of mass. Either the right side of the couch or the right end table could have served as the first fuel ignited and resulted in the total damage witnessed inside the compartment.

The most noteworthy damage is the deep calcination measurements behind the right end table, the near complete loss of mass to the right end table, and the progression of fire travel across the sofa from the right end should lead the investigator to the right end table as the first fuel ignited.

Comparison between Tests

Test two clearly was exposed for a longer duration to elevated temperatures and burned for a longer duration compared to test one. This is obviously due to the initial fuels having significantly different heat release rate curves.

Test one had a 60 second span between the breaking of the single pane glass window and flashover, while test two had an approximately 170 second delay. This longer duration of ventilation-controlled conditions in test two may have resulted in more combustion near the doorway and airflow entering the compartment, which may be the cause for greater damage and deeper calcination along the west wall and around the door.

Controlling the duration of post-flashover burning was a priority in each of the tests. Successfully, the timing between flashover and suppression was maintained at approximately 60 seconds for both tests. Therefore, the differences in location and magnitude of damage cannot be derived from any differences in post-flashover burning duration.

The maximum recorded temperatures for both tests were roughly the same, however, the temperature profile for test two exceeded 300^{o}C for approximately 300 seconds longer than test one. This extended duration of high temperatures led to slight differences in the visible and measurable damage noted post-fire. Most notably was the significantly greater surface area of clean burn damage in test two. However, the location and the relative magnitude of damage remained consistent between tests, except at the origin. There was a 20 kW/m^2 difference between test one and two. This was most likely due to the transducer being closer to the initial fuel items in test two.

The south wall in both tests had the greatest depth measurements, the greatest surface area of calcined wallboard, and the greatest clean burn damage. The sofa in both tests had significantly greater damage than the loveseat. The only other area of significant damage within the compartment was those areas adjacent to the door. This damage, however, should have easily been dismissed due to their relative location to an area of open ventilation in a compartment fire that was clearly ventilation-controlled for a period of time.

In defining the boundaries of the origin to a more distinct area along this wall, the analyst would want to look more closely at the depth of calcination measurements, relative damage to each content, and degree of damage between contents. The heat and flame vector analysis for both tests had several of the same effects and therefore had several vectors that were similar in direction and location. Test one clearly indicated that the area of origin was the center of the sofa. Test two at first glance appears to be very similar to test one. However, when taking a closer examination of test two, the progression of damage along the contents and the depth of calcination results all pointed the analyst back to the right end table.

CONCLUSIONS

This experimental series was designed to determine whether the initial damage caused by a lower heat release rate fuel persists after the involvement of a significantly higher heat release rate fuel. The more important question was whether the damage would persist to the point where fire investigators can effectively use the remaining data to arrive at an accurate origin? This study revealed that both visible and measurable damage associated with the area of origin persisted through full-room involvement and the involvement of secondary, higher heat release rate fuels. Clearly, the investigator would be able to identify the correct area of origin based on the available data remaining in these tests. It should be noted here, however, that these findings should not be extrapolated to all fires.

The physical evidence of the lower heat release rate fuel was not obscured in these tests possibly due the following reasons. First and foremost, as the fire started here, this area is exposed to the longest duration of combustion increasing the cumulative heat flux received by the area immediately intimate with the origin of the fire. This finding was anticipated, as fire patterns are representations of the material’s cumulative heat flux. Secondly, the initial development of the lower heat release rate fires did not significantly deplete the oxygen within the compartment and burned predominantly in a fuel-controlled state. Therefore, the early stages of the fire consisted of combustion predominantly at the fuel package with the production of relatively small quantities of combustion byproducts minimizing the effects on the rest of the room. However, once the fire spread to the higher heat release rate item (i.e. the sofa), the fire quickly became ventilation controlled, minimizing the amount of combustion actually taking place at the fuel package itself. At this point during the fire, the pyrolyzates underwent combustion wherever the fuel/oxygen mixture was correct, typically near the ventilation source. The damage at the doorway and along the west wall was consistently witnessed in all of the living room experiments, which can be attributed to this combustion of suspended pyrolyzates that originated from the sofa. Therefore, the heat flux anticipated from the sofa to obscure the initial damage was not witnessed to the extent expected due to the ventilation-controlled conditions.

All tests have yielded enough evidence to accurately and reliably reach the correct area of origin and supported the assertion that fire patterns persist regardless of the initial fuel package. In these tests, it was found that proper documentation of the scene and a sound knowledge of fire dynamics, enabled the investigator to reach appropriate conclusions regarding the origin of the fire utilizing fire patterns.

Additional testing will need to be conducted to evaluate whether the results found in this study can be extrapolated to compartments of larger volumes with taller ceilings, and/or in fires with significantly longer post-flashover burn times. Future testing will also vary the size of the ventilation openings possibly altering the witnessed damage.

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