Document Title:	Fire Dynamics and Forensic Analysis of Limited Ventilation Compartment Fires Volume 1: Experimental
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Document No.:	230164
Date Received:	April 2010
Award Number:	2007-DN-BX-K240

Fire Dynamics and Forensic Analysis of Limited Ventilation Compartment Fires
Volume 1: Experimental

Grant No. 2007-DN-BX-K240

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October 2009

ABSTRACT

Little research has been done to examine full-scale unventilated fires despite their common occurrence and relevance. Many fire fatalities and unsuccessful arson events (i.e., the fire did not become fully involved) occur as a result of these types of fires; however, the majority of fire testing has been conducted with ample ventilation to allow fires to grow to flashover and sustain fully-involved burning. This project was conducted to characterize the fire dynamics of unventilated and partially ventilated compartment fires. A series of fifteen full-scale fires were performed within an instrumented, four room, apartment style enclosure measuring 41.8 m^2 (450 ft^2). Three different fuel sources, including sofas, kitchen cabinets, and cotton batting, were tested using different ventilation schemes to analyze the effect of ventilation on fire growth and tenability. The results of these tests allowed for the examination of the effects of ventilation on general fire dynamics, including fire growth, smoke and gas production, and vitiation; tenability factors including temperature, heat flux and carbon monoxide FED levels; and the ability to utilize forensic tools to determine the cause and progression of a fire.

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EXECUTIVE SUMMARY

Little research has been done to examine full-scale unventilated fires despite their common occurrence and relevance. Many fire fatalities and unsuccessful arson events (i.e., the fire did not become fully involved) occur as a result of these types of fires; however, the majority of fire testing has been conducted with ample ventilation to allow fires to grow to flashover and sustain fully-involved burning. Work under a previous NIJ grant established a technical baseline for a limited number of unventilated fire scenarios that were ultimately ventilated and allowed to grow to flashover (Mealy & Gottuk, 2006(a); Mealy & Gottuk, 2006(b); Mealy C. L., 2007). Because of ventilating to flashover, the previous work did not allow the evaluation of forensic analysis methods for fires that remain unventilated or limitedly ventilated. The test results of the study also showed that unventilated phases of wood cabinet fires produced untenable toxic gas environments; but, for the upholstered furniture (sofa) fires, untenable gas concentrations did not occur until the fire was ventilated and approached flashover. However, the unventilated portions of the sofa fires were less than 30 minutes. This project builds on this previous study and expands the fundamental understanding of the fire dynamics, evaluates the utility of forensic tools, and validates a commonly used fire dynamics model (FDS) for a range of ventilation-limited fires, including accelerated (i.e., arson-type fires) and non-accelerated fires. The results of the model validation are presented in a separate report (Boehmer, Floyd, & Gottuk, 2009).

A series of fifteen full-scale fires were performed within an instrumented, four room, apartment style enclosure measuring 41.8 m^2 (450 ft^2). The interior dimensions of the test enclosure were 9.27 m (30 ft 5 in) by 4.51 m (14 ft 9.5 in). The height of the enclosure was 2.44 m (8 ft). The enclosure was divided into four separate rooms, which are referred to as the living room (LR), the dining room (DR), the kitchen (K), and the bedroom (BR). Separating the K and DR as well as the K and BR was a 0.91 m (3 ft) x 2.03 m (6 ft 8 in) opening. The DR and LR were open to one another except for a 0.31 m (1 ft) soffit extending down from the ceiling. The enclosure was instrumented with thermocouples, heat flux gauges, pressure transducers, optical density meters (ODMs), gas sampling, bi-directional probes, and a load cell on which the fuel was placed.

Three different fuel sources, including sofas, kitchen cabinets, and cotton batting, were tested using different ventilation schemes to analyze the effect of ventilation on fire growth and tenability. The cotton batting was a smoldering test with no ventilation and the fuel load was placed in the bedroom area of the enclosure at floor level. The sofas were tested under smoldering, non-accelerated flaming, and accelerated flaming conditions, and the tests were performed in the living room of the enclosure. All sofa smoldering tests had no ventilation, the non-accelerated flaming tests were performed with no ventilation, 0.012 m^2, and 0.24 m^2 window vents in the bedroom, and the accelerated flaming test had a window ventilation size of 0.12 m^2. The cabinets were tested under non-accelerated flaming conditions, and were placed both at floor level and at an elevated position within the kitchen area. The cabinets were all tested with no ventilation, a 0.12 m^2 bedroom vent, and a 1.85 m^2 door vent, and the elevated cabinets were also tested with a 0.67 m^2 bedroom window vent.

The results of these tests allowed for the examination of the effects of ventilation on general fire dynamics, including fire growth, smoke and gas production, and vitiation; tenability

factors including temperature, heat flux and carbon monoxide FED levels; and the ability to utilize forensic tools to determine the cause and progression of a fire.

Fires without enough ventilation became vitiated and ceased to grow (and sometimes extinguished), while fires with enough ventilation continued to grow. A critical ventilation size that allows the continued growth of a fire was determined. Based on these tests and previous work, the critical size for the sofa fires is close to or just larger than a full open window (0.24 m^2). All sofa tests with less ventilation became vitiated and self-extinguished. For the low cabinets, the critical ventilation size can be bracketed between the half open window ventilation (0.12 m^2) and the open door ventilation (1.85 m^2). For the high cabinets, it can be bracketed between the half open window and the window removed (0.67 m^2). Below this critical ventilation size, the cabinet fires continued to become vitiates (i.e., reduced oxygen concentration) and became suppressed. However contrary to the sofa fires, the cabinet fires rekindled and grew after being suppressed once the oxygen level at the base of the fire reached a critical value. Some of the cabinet fires had several peaks in fire growth over several hours. Each peak was accompanied by a sharp rise in temperature and carbon monoxide concentrations.

The suppression of fires was caused due to the reduction of oxygen and the increase in diluents, particularly carbon dioxide. Below a given oxygen concentration, a fire will not be able to burn. This concentration is characterized as the lower oxygen index (LOI). The LOI was determined experimentally for each test that vitiated and self suppressed. This was achieved by examining oxygen concentration at the base of the fire at times when the upper layer oxygen and temperature sharply changed, indicative of a change in the burning of the fuel. For example, when the temperature at the ceiling suddenly dropped, this signified that the fire was being suppressed and going out. It was found that the sofa had an approximate LOI of 18-19% oxygen and the cabinets had an LOI of approximately 16% oxygen. This experimental data was then compared to values calculated using Beyler's Unified Model of Fire Suppression (Beyler, 1992), based on the fire point theory. The values calculated from the fire suppression model were in general agreement with the experimental values. This validation of the of the fire point theory method demonstrates that the LOI data from this study and the unifired model of fire suppressioncan can be used in analyzing other real world fires that occur in different size structures and with different fires. This modeling tool can aid investigators in determining when or if a fire became underventilated.

Although ventilation ultimately influenced how large a fire could grow (i.e. peak heat release rate and temperature, whether a fire would vitiate and self suppress), the ventilation opening did not have an effect on the initial fire growth rate. For approximately the first 5-10 minutes after the ignition of the main fuel item, the heat release rate for each test was very similar to others of the same fuel type and orientation, regardless of the vent opening. This indicates that the initial fire growth rate for an open enclosure that is greater than 41.8 m^2 (450 ft^2) is not significantly affected by ventilation openings. As an enclosure becomes smaller, ventilation area will become more of a limiting factor.

Ventilation had a noticeable effect on tenability. In general, the fires became more hazardous with ventilation than without, sustaining untenable temperatures longer and reaching untenable CO exposures sooner. For no ventilation, sofa and low cabinet fires, thermal hazards generally preceded CO hazards in the areas proximate to the fire, while in remote areas the temperatures remained tenable and hazardous levels of CO developed. With ventilation, these fires produced CO and thermal hazards at approximately the same time, with conditions lasting longer than with no ventilation. For high cabinet fires, thermally untenable conditions were not reached throughout the compartment for no ventilation and half open window ventilation tests; however untenable CO levels were present. For greater ventilation sizes, the high cabinets created thermal and CO hazards at approximately the same time, similar to the sofa and low cabinet fires.

In terms of fuel source, sofa fires posed a faster thermal hazard than the cabinet fires, resulting in shorter times to untenable temperatures (~14-15 min. v. ~18-27 min.) and higher peak temperatures. There was no consistent trend of whether sofa or cabinet fires developed untenable CO hazards quicker; it depended on ventilation and location of the cabinets (high or low in the space). All the fires produced lethal CO levels in about 15 to 30 minutes.

The ignition scenario also had an effect on the time to untenable conditions within the enclosure. Smoldering fires posed no thermal hazard, and took much longer to reach untenable CO levels as opposed to the two flaming scenarios (generally on the order of hours as opposed to 15-30 minutes for non-accelerated flaming fires). Accelerated flaming ignition reached tenability criteria much faster than the non-accelerated scenario (1-3 min v 13-15 min); however, the class A non-accelerated flaming fire had higher temperatures and longer durations of untenable temperatures than the accelerated fire.

Soot deposition can play a key role in forensic analysis of compartment fires. As is typical with sufficient ventilation, the wall and ceiling areas around the fuel source were characterized by clean burns, where the soot was burned off of the surface. The size of the clean burn area is proportional to the size of the fire, which depends on the ventilation. Generally for these tests, the less ventilation a test had, the more soot was deposited on the carpet within the enclosure. Also, soot deposition can be used to aid in the area of origin determination. It was observed that the walls in the fire room had clear demarcation and very dark soot deposits in the upper portion of the room. Further from the fire room, the demarcation lines were not as clear and the soot deposits were much lighter and more uniform floor to ceiling.

Smoldering fires produced little to no visible soot deposition throughout the enclosure, while flaming fires generally coated all surfaces with varying levels of soot. Therefore, distinguishing between a smoldering fire and a flaming fire proved to be relatively easy. Distinguishing between an accelerated and non-accelerated fire in under-ventilated conditions proved to be more difficult. Both the accelerated and non-accelerated fires produced similar fire patterns and soot deposition on the walls. Approximately the same amount of fuel was consumed during each test, leaving the same general fire pattern on the sofas. The only obviously distinguishing feature that differentiated the accelerated and the non-accelerated fire was the trailer pattern that was left on the floor. Chemical testing for ignitable liquid residue was ineffective at determining the presence of ignitable liquids on various sofa samples.

In summary, this research provides new insight into the effects of ventilation on various fire dynamics, tenability, and forensic analysis of limited ventilation enclosure fires. Further research in this area would enhance the knowledge of these effects. Due to the limited amount of tests in this research, no tests were performed multiple times. Doing so would further validate the findings of this research and the applicability of the findings. In addition, the limited amount of ventilation sizes used limited the effectiveness of fully determining the critical ventilation size needed to sustain the growth of a fire. Finally, research on larger enclosures and multiple story structures would further enhance the knowledge of fire development, tenability effects and the applicability of the unified suppression model to extrapolate data to other fire scenarios with limited ventilation. In particular, a two story structure may allow longer fire development and increased thermal and toxic gas exposures to upper floor occupants even for unventilated enclosures of the same floor area as a single story structure. This would be due to the filling effect of upper levels while allowing the fire to remain in the lower layer. However, local ventilation restrictions, such as interior doors to the fire room, may still act to vitiate the environment near the base of the fire and partially suppress the fire. More work is needed to develop a full understanding of these different effects and the validation and use of the unified suppression model for larger and multiple story structures.

1 INTRODUCTION

1.1 Background

Little research has been done to examine full-scale unventilated fires despite their common occurrence and relevance. Many fire fatalities and unsuccessful arson events (i.e., the fire did not become fully involved) occur as a result of these types of fires; however, the majority of fire testing has been conducted with ample ventilation to allow fires to grow to flashover and sustain fully-involved burning. Although several research programs (Hill & Milke, 1996; Babrauskas, 1979; Quintiere, 1982) have documented full-scale enclosure fire dynamics and others (Shanley, 1997; Putorti, 1997; Putorti, 2001) have conducted full-scale fire tests to examine fire patterns, little research has been done to examine full-scale unventilated enclosure fires and resultant fire effects and patterns. Work under a previous NIJ grant established a technical baseline for a limited number of unventilated fire scenarios that were ultimately ventilated and allowed to grow to flashover (Mealy & Gottuk, 2006(a); Mealy & Gottuk, 2006(b); Mealy C. L., 2007). Because of ventilating to flashover, the previous work did not allow the evaluation of forensic analysis methods for fires that remain unventilated. The test results of the study also showed that unventilated phases of wood cabinet fires produced untenable toxic gas environments; but, for the upholstered furniture (sofa) fires, untenable gas concentrations did not occur until the fire was ventilated and approached flashover. However, the unventilated portions of the sofa fires were less than 30 minutes. The data indicates that if the fires had not been manually ventilated, carbon monoxide levels would have likely led to untenable conditions over prolonged, unventilated fire scenarios, which are commonly encountered by fire investigators. Therefore, it is important to understand how these fires develop and to be able to quantitatively characterize these fire environments, relative to post-fire scene examination and victim injury and toxicology examinations. This project builds on this previous study and expands the fundamental understanding of the fire dynamics, evaluates the utility of forensic tools, and validates a commonly used fire dynamics model (FDS) for a range of ventilation-limited fires, including accelerated (i.e., arson-type fires) and non-accelerated fires.

This research program was conducted under a grant from the National Institute of Justice to characterize the fire dynamics of unventilated and partially ventilated compartment fires. A series of full-scale enclosure fire tests were conducted at the Bureau of Alcohol, Tobacco and Firearms (ATF) Fire Research Laboratory (FRL). The results and conclusions of the experimental portion of the research program are presented in this report. The results of the model validation are presented in a separate report (Boehmer, Floyd, & Gottuk, 2009).

1.2 Objectives

The principle objective of this experimental research was to determine the effects that ventilation has on both fundamental fire dynamics and tenability. In addition, this research sought to evaluate the utility of forensics tools for fire scene analysis.

1.3 Approach

The objectives of this research were achieved by way of full scale experiments. The experiments were performed within an instrumented, four room, apartment style enclosure measuring 41.8 m^2 (450 ft^2). Figure 1-1shows a general schematic of the test enclosure. Three different fuels sources were tested using different ventilation schemes to analyze the effect of ventilation on fire growth and tenability. A total of fifteen full-scale experiments were performed. The enclosure and instrumentation of the enclosure were in general accordance to ASTM 603-07, “Guide for Room Fire Experiments” (ASTM E 603-07, 2007).

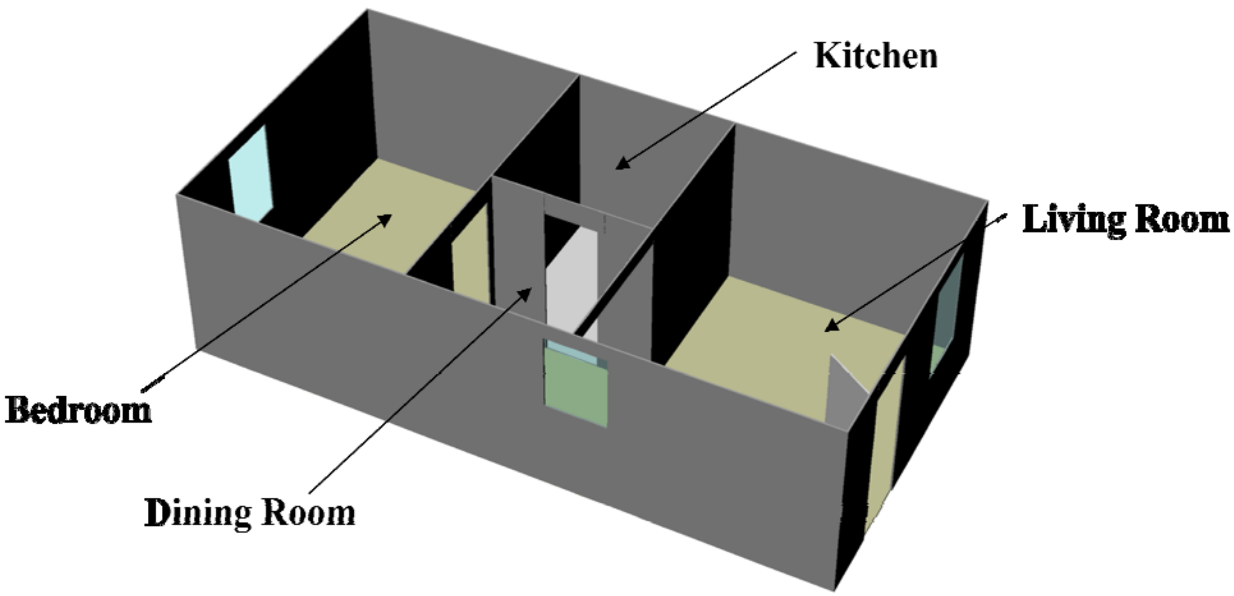


Figure 1-1. General Schematic of Enclosure

2 EXPERIMENTAL PLAN

Table 2-1shows a list of all tests performed during the test series, along with information on location, fuel load, ventilation, and ignition scenario. In total, two calorimetry tests, two burner tests, four smoldering tests, four flaming sofa tests, and seven flaming cabinet tests were performed. Each test had a unique ventilation and ignition scenario. Other than the front door, all ventilation refers to the status of the bedroom window.

Table 2-1. Test Matrix

Test Matrix					
Test ID	Fire Type	Fuel	Ignition Source	Source Location	Vent. Scheme
CAL1	Calorimetry	Sofa	Tissue Boxes	Calorimetry Hood	N/A
CAL2	Calorimetry	Cabinets	Tissue Boxes	Calorimetry Hood	N/A
B1	Flaming	Nat. Gas	125 kW Burner	Living Room	No Ventilation
B2	Flaming	Nat. Gas	125 kW Burner	Living Room	Full Open Window
SM1	Smoldering	Cotton Batting	Cartridge Heater	Bedroom	No Ventilation
SM2	Smoldering	Sofa	Cartridge Heater	Living Room	No Ventilation
SM3	Smoldering	Sofa	Cartridge Heater	Living Room	No Ventilation
SM4	Smoldering	Sofa	Cartridge Heater	Living Room	No Ventilation
S1	Flaming	Sofa	Tissue Boxes	Living Room	No Ventilation
S2	Flaming	Sofa	Tissue Boxes	Living Room	Full Open Window
S3	Flaming	Sofa	Tissue Boxes	Living Room	Half Open Window
S4	Accelerated Flaming	Sofa	Gasoline	Living Room	Half Open Window
CL1	Flaming	Low Cabinets	Tissue Boxes	Kitchen	No Ventilation
CL2	Flaming	Low Cabinets	Tissue Boxes	Kitchen	Half Open Window
CL3	Flaming	Low Cabinets	Tissue Boxes	Kitchen	Open Door
CH1	Flaming	Elevated Cabinets	Tissue Boxes	Kitchen	No Ventilation
CH2	Flaming	Elevated Cabinets	Tissue Boxes	Kitchen	Half Open Window
CH3	Flaming	Elevated Cabinets	Tissue Boxes	Kitchen	No Window
CH4	Flaming	Elevated Cabinets	Tissue Boxes	Kitchen	Open Door

2.1 Fuel Load Calorimetry

Initial testing was performed to determine the manner in which the selected fuel loads would burn and to measure the heat release rates. Both the cabinet assembly and the sofa were burned under a 1 MW hood calorimeter, using the class A "accidental" flaming ignition scenario (see Section 3.5.2). The fuel items were assembled and placed on the same load cell as used in the compartment tests. The main outputs from these calorimetry tests were the measured heat release rates and mass loss rates. Using these values, an approximate heat of combustion for the fuels was determined. Each calorimetry test was performed twice.

2.2 Compartment Tests

2.2.1 Gas Burner Tests

The goals of the gas burner tests were to demonstrate that all of the instrumentation was working correctly and to provide a baseline for the behavior of a fire within the compartment. Two 125 kW burner tests were performed in the living room (LR). One test was performed with no ventilation and the other with a full open window. These tests represented well characterized and controlled fires with known heat release rates. Therefore, they served as good baseline cases for model comparisons.

2.2.2 Fire Tests

The fire tests utilized realistic sources, such as sofas, cabinets and cotton batting, and they were designed to examine the effects of ventilation and ignition scenario in relation to tenability, fire growth, and fire sustainability. Five different ventilation conditions were examined, ranging from an open door or window to no vent openings other than natural leakage into the space. Ignition scenarios ranged from smoldering fires with heating elements to flaming fires with small class A ignition scenarios and gasoline.

3 EXPERIMENTAL DESIGN

3.1 Test Facility

The experimental tests for this study were performed at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) National Laboratory Center. The calorimetry tests were performed in the ATF Fire Research Lab (FRL) Medium Burn Room under a 1MW square calorimeter hood. The Compartment Tests were performed in the FRL Large Burn Room.

3.2 Enclosure

3.2.1 Enclosure Dimensions

The interior dimensions of the test enclosure were 9.27 m (30 ft 5 in) by 4.51 m (14 ft 9.5 in). The height of the enclosure was 2.44 m (8 ft). The enclosure was divided into four separate rooms, which are referred to as the living room (LR), the dining room (DR), the kitchen (K), and the bedroom (BR). This naming convention, as well as the dimensions of the four rooms, can be seen in Figure 3-1. Separating the K and DR as well as the K and BR was a 0.91 m (3 ft) x 2.03 m (6 ft 8 in) opening. The DR and LR were open to one another except for a 0.31 m (1 ft) soffit extending down from the ceiling. As shown in Figure 3-1, the walls of the enclosure were given a naming convention to minimize confusion. A detailed plan of the enclosure can be found in Appendix 0.

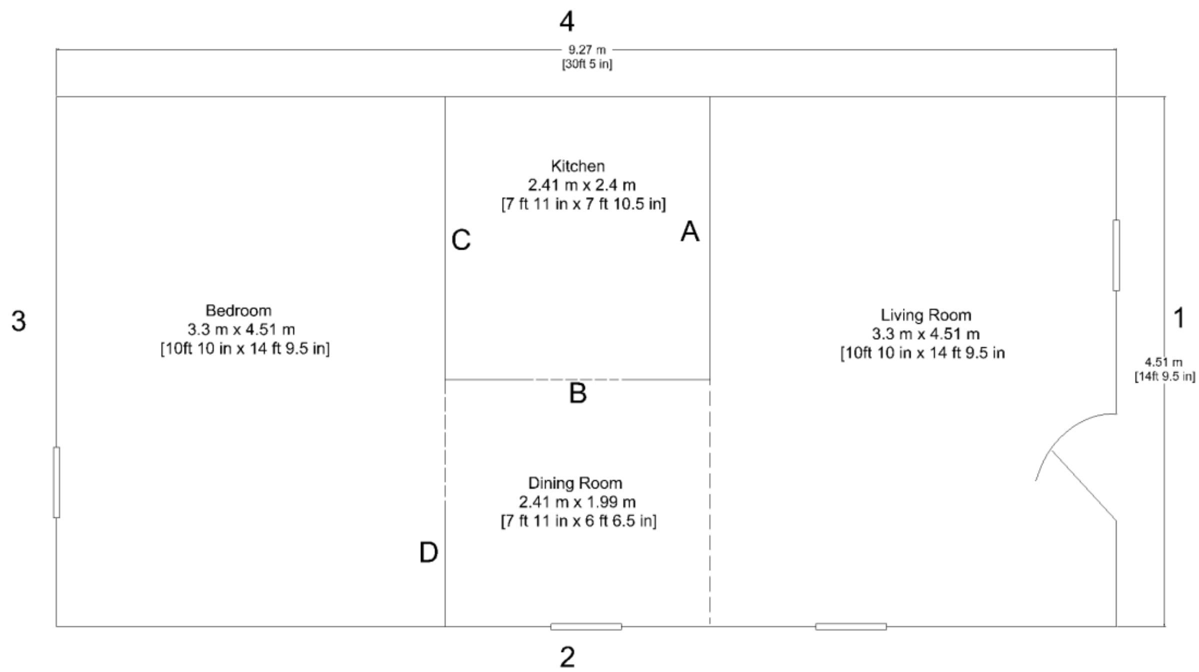


Figure 3-1. Plan View of Enclosure

3.2.2 Enclosure Construction

Enclosure walls, both interior and exterior, were constructed from 2 x 4 wood framing. Floor and ceiling joists were 2 x 10s spanning the width of the enclosure. Exterior walls consisted of two 0.016 m (5/8 in) sheets of Type X gypsum wallboard (GWB). The ceiling was constructed using a single layer of 0.016 m (5/8 in) GWB. The sub-floor consisted of a base layer of 0.013 m (1/2 in) plywood with a 0.013 m (1/2 in) GWB overlay. Carpet was then laid over the subfloor in the LR, DR and BR. The K had no additional flooring over the sub-floor. Interior walls consisted of a single layer of .013 m (1/2 in) GWB. Gypsum sheets were staggered on all surfaces containing more than one layer of GWB in order to minimize the influence of seams. Joint compound and joint tape were used to seal all seams present on interior wall surfaces. Two coats of flat paint were used as interior finishing.

Four double-pane, double-hung windows (American Craftsman 3000 series), measuring 0.6 m (2 ft) by 1 m (3 ft 4 in), were installed in the enclosure. Also, five camera viewports measuring 0.25 m (10 in) by 0.25 m (10 in) were installed in the exterior walls. An exterior door measuring .91 m (3 ft) by 2.03 m (6 ft 8 in) was installed in Wall 1. The dimensioned positions of these windows and doors can be found in Appendix 0.

3.3 Ventilation Scenarios

A total of five ventilation scenarios were used during this test series. The ventilation scenarios, their naming conventions, and area of ventilation, are presented in Table 3-1. The opening height dimensions of the full open and half open window scenarios were measured from the raised lip on the window sill to the base of the bottom window pane (see Figure 3-2). The first ventilated fire (test S2) had a full open window. After this test was conducted, there was concern that the ventilation was too much and may lead to flashover conditions. Therefore, the following tests used the half open window configuration.

Table 3-1. Ventilation Scenarios

Description	Naming Convention	Vent Dimensions	Vent Area, m^2 [ft^2]
No ventilation	No Ventilation	N/A	N/A
BR window open 0.20 m [8 in]	Half Open Window	0.20 m x 0.58 m [8 in x 1 ft 11 in]	0.12 [1.28]
BR window open 0.41 m [16 in]	Full Open Window	0.41 m x 0.58 m [1 ft 4 in x 1 ft 11 in]	0.24 [2.56]
BR window removed	No Window	1.03 m x 0.65 m [3 ft 4.5 in x 2 ft 1.5 in]	0.67 [7.17]
Open door, all windows closed	Open Door	0.91 m x 2.03 m [3 ft x 6 ft 8 in]	1.85 [20]

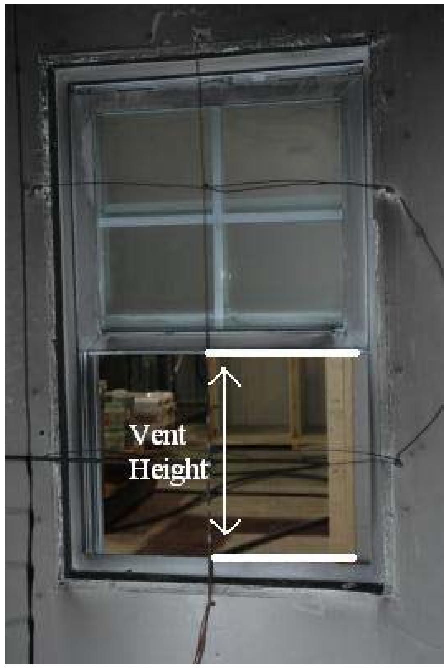


Figure 3-2. Vent height orientation

3.4 Fuel Sources

3.4.1 Sofa tests

For the sofa tests, the ignited fuel source was an upholstered sofa. Addition furniture was added to the enclosure as targets and for use as secondary fuel sources.

3.4.1.1 Sofa

The sofa used in these tests was an IKEA, Klippan style sofa. The overall dimensions of the sofa were 1.8 m (5 ft 10 in) wide by 0.88 m (2 ft 11 in) deep by 0.66 m (2 ft 2 in) high. The seat depth was 0.54 m (1 ft 9 in) and the seat height was 0.43 m (1 ft 5 in). The frame of the sofa was constructed of particleboard, solid hardwood, solid softwood, and cardboard. The sofa had steel zig-zag springs. The sofa seat, back and armrest were constructed of 91% polyurethane foam (density of 30 kg/m^3) and 9% polyester wadding. The lining and cover were 100% cotton. The sofa met the requirements of the California Bureau of Home Furnishings Technical Bulletin 117.

3.4.1.2 Additional Furniture

For the living room sofa tests, an armchair and coffee table were present in addition to the sofa. The armchair was an IKEA, Ektorp Tullsta style chair. The coffee table was an IKEA, Lack style coffee table. The overall dimensions of the chair were 0.80 m (2 ft 8 in) wide by 0.72 m (2 ft 4 in) deep by 0.78 m (2 ft 7 in) high. The seat dimensions were 0.50 m (1 ft 8 in) wide by 0.47 m (1 ft 7 in) deep by 0.43 m (1 ft 5 in) high. The frame was constructed of expanded polystyrene plastic, solid beech, particleboard, plywood, polyurethane foam and polyester wadding. The seat and back cushions were constructed of polyurethane foam and polyester wadding. The seat cover was 100% cotton.

The overall dimensions of the coffee table were 0.90 m (2 ft 11 in) by 0.55 m (1 ft 10 in) by 0.45 m (1 ft 6 in). The top of the coffee table was constructed of particleboard, ABS plastic and acrylic paint. The shelf was constructed of particleboard, ABS plastic and melamine foil. The legs were constructed of particleboard and foil.

The coffee table was positioned so that the long edge was 0.61 m (2 ft) from the edge of the sofa, and centered with respect to the sofa. The chair was placed in the corner of Wall 1 and Wall 4, such that the sides of the chair were both at a 45 degree angle from either wall, with the back of the chair touching both walls.

3.4.2 Cabinet Tests

The cabinets used for the kitchen tests were Kitchen Kompact, Chadwood 2, 18W style cabinets. The overall dimensions of each cabinet were 0.76 m (2ft 6 in) high by 0.46 m (1 ft 6 in) wide by 0.31 m (1 ft) deep. The cabinets were constructed of an oak frame and door with plywood end panels. Each cabinet had 3 shelves consisting of the cabinet interior base and two adjustable height shelves. The shelves were spaced so that each shelving area was equal and had a height of approximately 0.23 m (9 in).

For each test, a total of four cabinets were installed side by side, as seen in Figure 3-3. These cabinets were mounted using 0.064 m (2.5 in) drywall screws, which were screwed into the molding at the top and bottom of the back of the interior of the cabinets. In addition, the cabinets were anchored together by two 0.064 m (2.5 in) drywall screws, positioned near the top and bottom of the cabinet front face framing.

Figure 3-3. Cabinet array with ignition source

Additional fuel was added to the two leftmost cabinets. Figure 3-4 shows a photo of the setup. The fuel load within the cabinets consisted of three unopened Georgia Pacific Preference brand paper towel rolls, three empty and three unopened Kleenex brand tissue boxes, and 24, 355 mL Dart brand polystyrene cups. The cups were in twelve stacks of two as shown in Figure 3-3.

The tissue boxes alternated between empty and full, with two full on the bottom shelf and two empty on the middle shelf. The remaining two cabinets were empty.

Figure 3-4. Cabinet Fuel Load

3.4.3 Cotton Batting Tests

To simulate bedding material, a folded section of 100% cotton batting was used. In general, developing self-sustained smoldering of new commercial products can be very challenging, particularly with cigarettes which are more commonly required to meet new fire-safe test standards. For these smoldering tests, electric cartridge heaters were used as the ignition source. Initially, comforters purchased from a retail store were evaluated for a smoldering bedding scenario. However, sustained smoldering was not achievable. Therefore, the use of cotton batting was used as a bounding source for bedding, since it has been established in prior works as a reliable medium for obtaining self-sustaining smolder with significant carbon monoxide production. In order to have a test that would last multiple hours, a large quantity of cotton batting (36 m^2 (384 ft^2)) was used and folded into a thick pile. It is expected that this source material and configuration may bound many actual bedding products in ease of smolder, duration of smolder and CO production.

The batting was Warm and Natural needled cotton batting, produced by The Warm Company. The batting was folded to produce a rectangular pile 0.91 m (3 ft) wide by 0.61 m (2 ft) deep by 0.17 m (6.5 in) high. The folded pile had 64 layers of cotton batting with a total mass of approximately 4.95 kg...

The initial size of the batting was 14.63 m (48 ft) by 2.44 m (8 ft). The thickness of the batting was approximately 0.0025 m (0.1 in). The material was folded to the final dimensions via the following steps:

Step 1: Fold batting to 14.63 m (48 ft) by 1.22 m (4 ft)
Step 2: Fold batting to 7.32 m (24 ft) by 1.22 m (4 ft)
Step 3: Fold batting to 3.66 m (12 ft) by 1.22 m (4 ft)
Step 4: Fold batting to 1.82 m (6 ft) by 1.22 m (4 ft)
Step 5: Fold batting to 1.82 m (6 ft) by 0.61 m (2 ft)
Step 6: Fold batting to 0.91 m (3 ft) by 0.61 m (2 ft)

3.5 Ignition Scenarios

3.5.1 Smoldering Scenario

To achieve smoldering conditions, two methods were used. For tests SM1, SM2, and SM3, a Vulcan Model TB507A 500 W cartridge heater was used. The heater had a diameter of 0.013 m (0.5 in) and a length of 0.127 m (5 in). The cartridge heater was powered at 60VAC with a variac (Staco Energy Products model 3PN1510). For test SM4, a Chromalox Model CIR-202N-K1 cartridge heater was used. The cartridge heater had a length of .05 m (2 in) and a diameter of .01 m (0.39 in). The cartridge heater was connected to a temperature regulator which was set to 449°C (840°F). The orientation of these heaters with respect to the fuel loads is addressed in Section 5.4.

3.5.2 Class A Flaming Scenario

To represent an accidental class A flaming source, two unopened tissue boxes with a small isopropyl alcohol ignition flame were used. A setup of this arrangement can be seen in Figure 3-5. Four (4) mL of isopropyl alcohol were poured into a 1 in. NPT pipe cap (internal diameter of 0.033 m (1.315 in)). This pipe cap was positioned in between two unopened Kleenex Brand tissue boxes, oriented vertically, with the bases facing each other. The tissue boxes were Kleenex Brand 2-ply tissues with box dimensions of 0.12 m (4.75 in) by 0.225 m (9 in) by 0.05 m (2 in). The pipe cap was positioned so that the exterior of the cap was flush with the leading edge of the tissue boxes. This scenario was initiated by igniting the isopropyl alcohol with a butane lighter.

The time to ignition for the tissue boxes was relatively repeatable, with a variance from test to test of less than 30 seconds. Once ignited, the alcohol flame typically burned for 6 minutes before the boxes were ignited. The box fire then typically burned for 2 minutes before reaching its peak. By itself, the source would generally burn for a total duration of 11 minutes with a peak heat release rate of2 to 3 kW.

Figure 3-5. Accidental flaming ignition scenario setup

3.5.3 Accelerated Flaming Scenario

A total of 1 L of gasoline was used to achieve accelerated flaming conditions; 0.75 L was poured on the center of the sofa at the same location as the box ignition scenario. A piece of upholstery fabric from another sofa was inserted in the gap between the sofa seat and back to prevent the gasoline from running off of the sofa since the seat and back cushions were fixed in place and did not make a tight connection. The remaining 0.25 L was used as a trailer poured on the floor from the sofa to the front door. This scenario was initiated by igniting the trailer with a propane torch at the front door. The front door was then immediately closed.

4 INSTRUMENTATION

Instrumentation typical to all tests is presented in this section. Any instrumentation specific to a single test is addressed in Section 0. In addition, smoke alarm data from testing, which is not included in this analysis, can be found in Appendix B.

4.1 Thermocouples

Thermocouples (TCs) were used to characterize the thermal environment within the enclosure. Locations of TCs can be found in Figure 4-1.

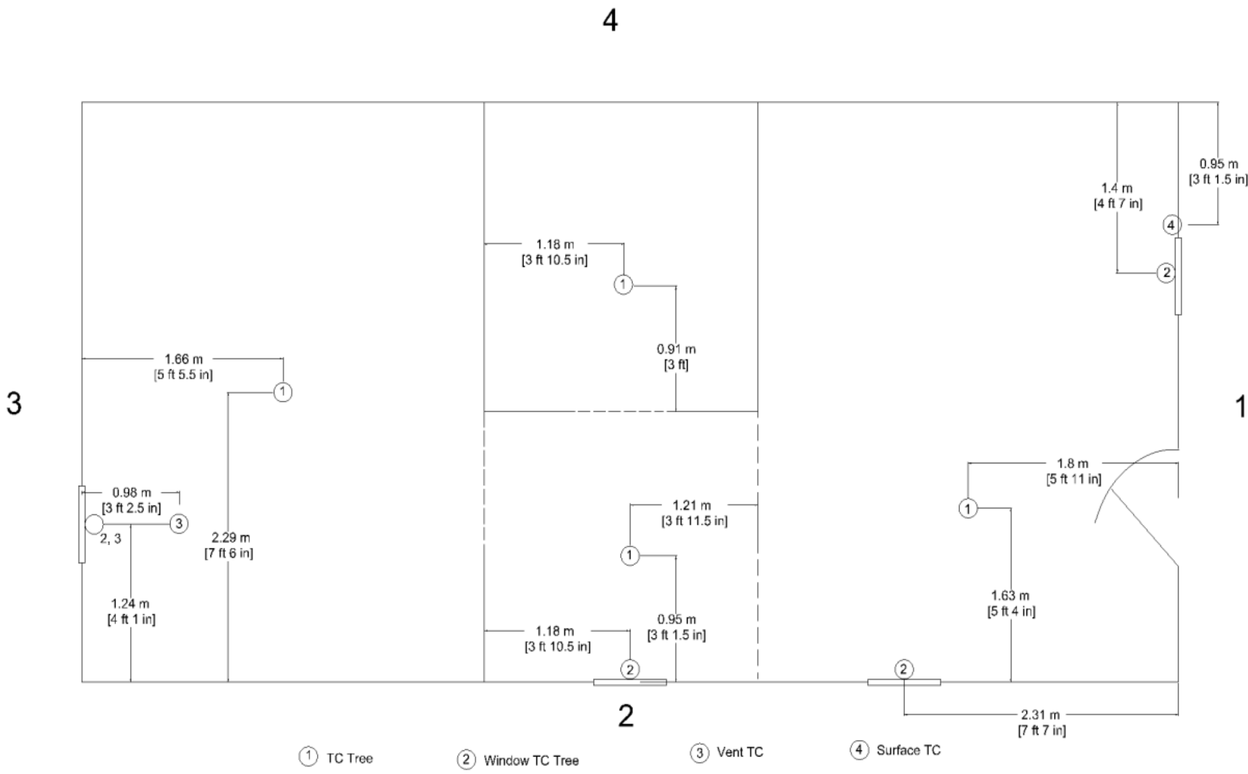


Figure 4-1. TC Locations

4.1.1 Thermocouple Trees

Four floor-to-ceiling thermocouple (TC) trees were used in these tests. Each tree had a TC positioned at elevations of 0.03 m (1 in), 0.31 m (1 ft), 0.61 m (2 ft), 0.91 m (3 ft), 1.22 m (4 ft), 1.52 m (5 ft), 1.82 m (6 ft), 2.13 m (7 ft) and 2.41 m (7 ft 11 in). A TC tree was present in each of the four rooms of the enclosure. The trees were typically centered in the space, except in the living room where the tree was positioned in the normal path of egress from the back of the apartment to the front door.

4.1.1.1 Bare Bead

The TC trees in the DR and BR were constructed of bare bead TCs. All bare bead TCs were 24Ga Type K with glass insulation.

4.1.1.2 Aspirated

The TC trees in the LR and K were aspirated thermocouple (ATC) trees. ATC trees were used because the aspiration and shielding design limit the radiation effects caused by the close proximity of the TC tree to the fire. Figure 4-2 shows a photograph of an ATC tree. The ATC trees used 0.062 m (1/16 in) diameter, inconel sheathed TC probes with exposed beads.

Figure 4-2. ATC tree

Figure 4-3 and Figure 4-4 show diagrams of the ATC tree construction. The trees were designed in general accordance with the single shield model described by Blevins and Pitts (Blevins & Pitts, 1999). The backbone of the ATC tree was constructed out of 0.013 m (0.5 in) black steel pipe. At each TC elevation, a 0.152 m (6 in) long section of 0.006 m (0.25 in) stainless steel tubing was connected to the backbone by a ‘T’ pipe fitting and a NPT to tubing reducer. A small hole was drilled into the back of each ‘T’ pipe fitting, and a probe TC was inserted through that hole until it was 0.05 m (2 in) from the end of the stainless steel tubing section.

Aspiration of the tree was provided by a Gast 1.5 HP rotary vane vacuum pump (model #7Z782) connected to the bottom of the tree. The top of the tree was capped to prevent leakage. An average aspiration airflow rate of 6.9 m/s (3.28 ft/s) over all probes was achieved using this setup. This flow velocity is above the minimum velocity of 5 m/s, as suggested in ASTM E 603-07 (ASTM E 603-07, 2007). Only the ATC tree in the room of fire origin was aspirated during a test. The other was plugged and served as a shielded TC tree.

In addition to the aspirated TCs, 3 non-aspirated probes were included on each ATC tree. These additional probes were located at 0.61 m (2 ft), 1.52 m (5 ft), and 2.41 m (7 ft 11 in). These TC probes were used for a comparison of aspirated vs. non-aspirated temperature readings.

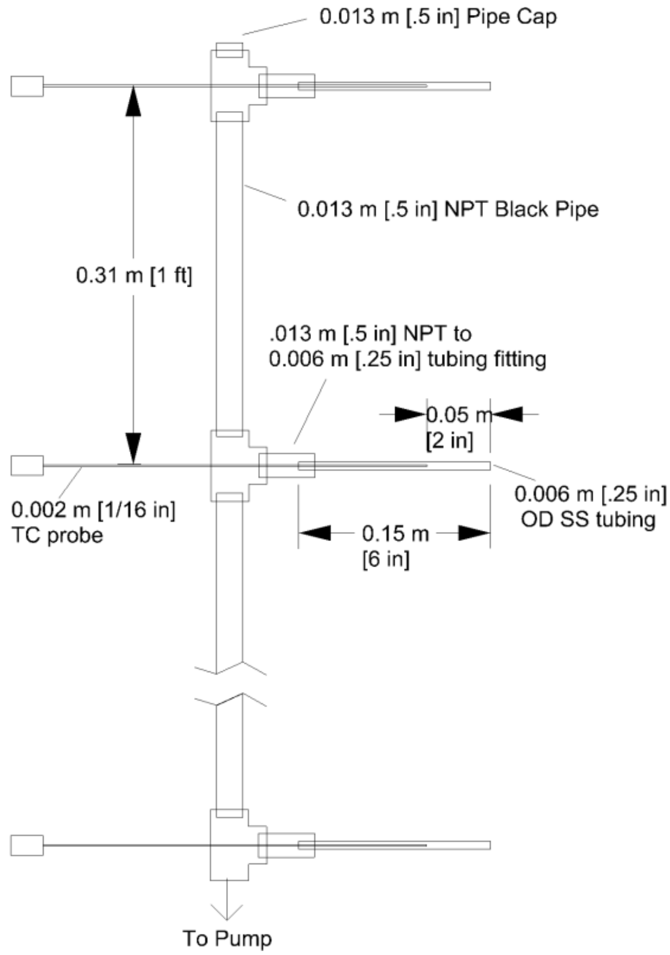


Figure 4-3. ATC Tree Detailed Layout

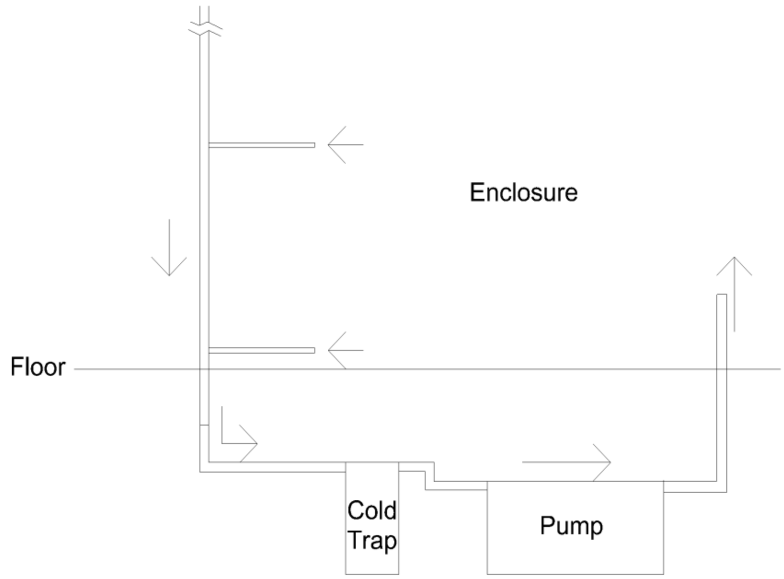


Figure 4-4. Flow Path of ATC Tree

4.1.2 Window Thermocouples

A bare bead TC was present at the center of the top and bottom panes of each window in the enclosure. The elevations of these TCs were 1.37 m (54 in) and 1.85 m (73 in). Each TC was positioned approximately 0.03m (1 in) from the surface of the window.

4.1.3 Vent Flow Thermocouples

During tests with window ventilation, two additional TC trees were present in the BR. These trees were located at the window and 0.97 m (3 ft 2 in) away from the window, along the center line of the window as shown in Figure 4-1 as a Vent TC. The distance from the window was determined by using 2.5 times the normalized diameter of the full open window ventilation area.

The elevations and number of TCs varied between ventilation schemes, as follows:

Table 4-1. Vent TC Elevations for Different Ventilation Schemes

Thermocouple I.D.	Vent Thermocouple Height (m)		
	Full Open Window	Half Open Window	Window Removed
1	1.21	1.18	1.16
2	1.28	1.23	1.28
3	1.33	1.28	1.41
4	1.38	1.33	1.53
5	1.44	N/A	1.66
6	1.51	N/A	1.79
7	N/A	N/A	1.92
8	N/A	N/A	2.04

4.1.4 Surface

For the sofa tests, two pairs of surface TCs were placed on the wall across the LR from the fire. Omega, 30Ga, Type K, Chromega-Alomega surface TC (part number SA1XL-K), with glass insulation were used for these tests. The TCs were self adhesive and mounted directly to the wall. Each pair consisted of a surface TC inside the structure, and a surface TC outside of the structure, directly opposite each other, mounted on the GWB. The elevations of these pairs were 0.61 m (2 ft) and 1.82 m (6 ft).

4.2 Heat Flux Transducers

Heat flux transducers were used in the enclosure to measure radiant heat flux from the fire and the smoke layer. The heat flux transducers used in this test series were manufactured by Medtherm Corporation. Two different models with different ranges were used. A 0-25 kW/m^2 transducer (model #64-2.5-36-21640) was used for all floor level locations. A 0-50 kW/m^2 transducer (model #64-5SB-36-21640) was used for wall-mounted and fire locations. Locations of all heat flux transducers can be found in Figure 4-5.

During testing, water was pumped through the heat flux transducers by a water heating system developed at ATF, which kept the water at approximately 30°-35°C (86°-95°F). Prior to each experiment, a two minute background data sample was collected. The results of this sample were input into the data acquisition, thus allowing the effects of the heated water to be zeroed during the actual experiment.

4.2.1 Floor Level

Floor level heat flux transducers oriented towards the ceiling were used to determine the amount of heat flux being emitted from the upper layer. These were located in each room of the enclosure and mounted so that the leading edge of the transducer was flush with the floor, leaving the remaining part of the transducer below the enclosure.

4.2.2 Wall-mounted

Two wall-mounted heat flux transducers were positioned at 0.61 m (2 ft) and 1.83 m (6 ft) elevations, directed toward the fire source. These transducers were mounted with the leading edge flush against the wall, so that the remainder of the transducer was outside the fire compartment. These heat flux transducers were used to help characterize the heat flux impinging on the walls of the test enclosure and were used for comparison to model simulation data. These transducers were collocated with the wall surface TCs during sofa tests, and positioned in Wall B for cabinet fire tests.

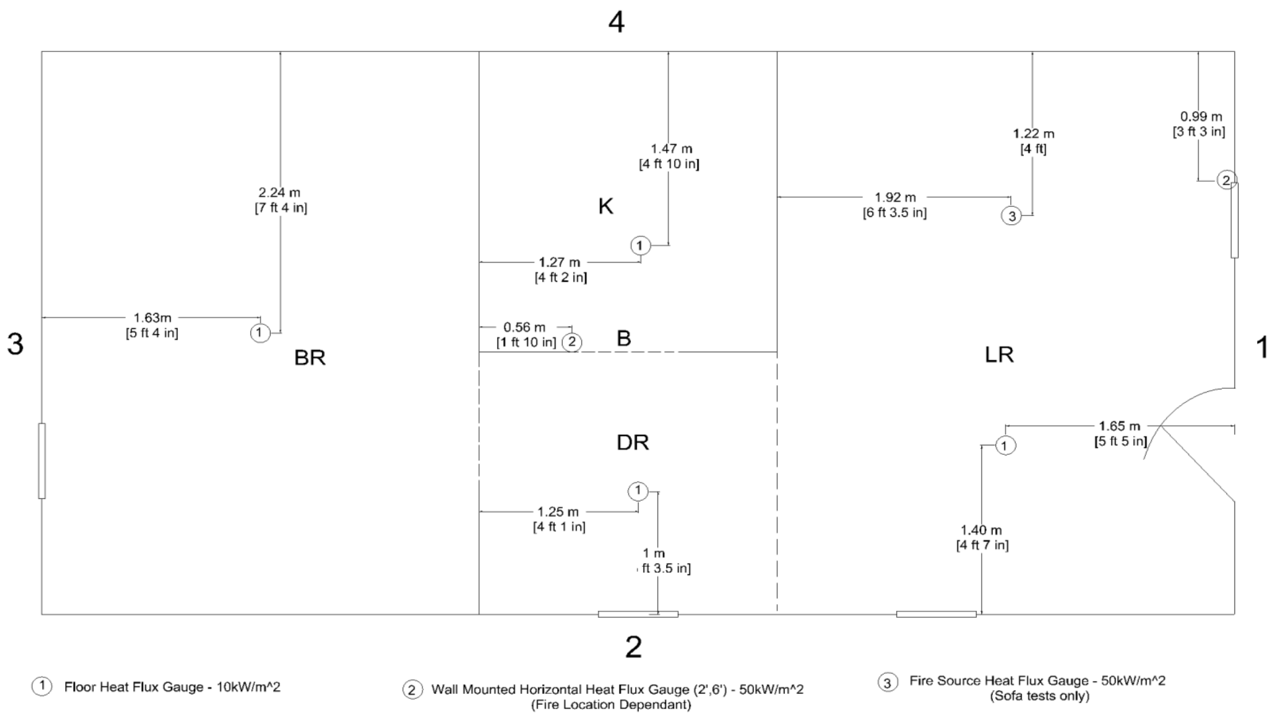


Figure 4-5. Heat Flux Transducer Locations

4.2.3 Fire Level

For sofa tests, an additional heat flux transducer was installed in the room of origin oriented horizontally toward the fire source. The transducer was mounted on a stand and positioned 1 m (3 ft 3 in) from the fire source at a height of 0.91 m (3 ft). The purpose of this transducer was to characterize the heat flux from the burning sofa as it would affect secondary items. This fire level heat flux transducer was not used during cabinet tests due to the close proximity of the wall mounted heat flux transducers.

4.3 Pressure Transducers

Pressure transducers were used to determine pressure differentials between the enclosure and ambient conditions. A total of thirteen pressure ports were used throughout the enclosure. Twelve of the ports were located at elevations of 0.31 m (1 ft), 0.91 m (3 ft), 1.52 m (5 ft), and 2.13 m (7 ft) in the LR, DR, and K. The final port was located on the floor near the base of the fuel source. The pressure ports were 0.31 m (1 ft) lengths of 0.006 m (0.25 in) diameter copper tubing, which protruded 0.03 m (1 in) into the enclosure. The copper ports were connected to the transducers by 0.006 m (0.25 in) diameter polyethylene tubing. Locations of these ports can be seen in Figure 4-6. The second pressure port of the transducer was connected to a section of polyethylene tubing that was mounted to the exterior of the enclosure at the same elevation to yield the pressure difference between the interior and exterior of the enclosure. The transducers used were MKS Instrument, Model 220DD-00001B2B transducers, with a range of 0-133.32 Pa.

Prior to each experiment, a two minute background data sample was collected. During this background period, the pressure transducers were cross-ported, creating a closed loop through the transducer so that a zero value is transmitted to the data acquisition system. This data was then input into the data acquisition system for use in the actual experiment as the transducers ambient reading.

4.4 Velocity Probes

Velocity probes were used to characterize gas flow velocities in the enclosure and vent area. Each velocity probe consisted of a bi-flow probe connected to a pressure transducer and a bare bead TC. The bi-flow probes had a diameter of 0.012 m (0.5 in) and were constructed per the McCaffrey and Heskestad design (McCaffrey & Heskestad, 1976). The pressure transducer and bare bead TC are the same type as previously discussed. The TC for each bi-flow probe was located 0.01 m (0.39 in) above the probe.

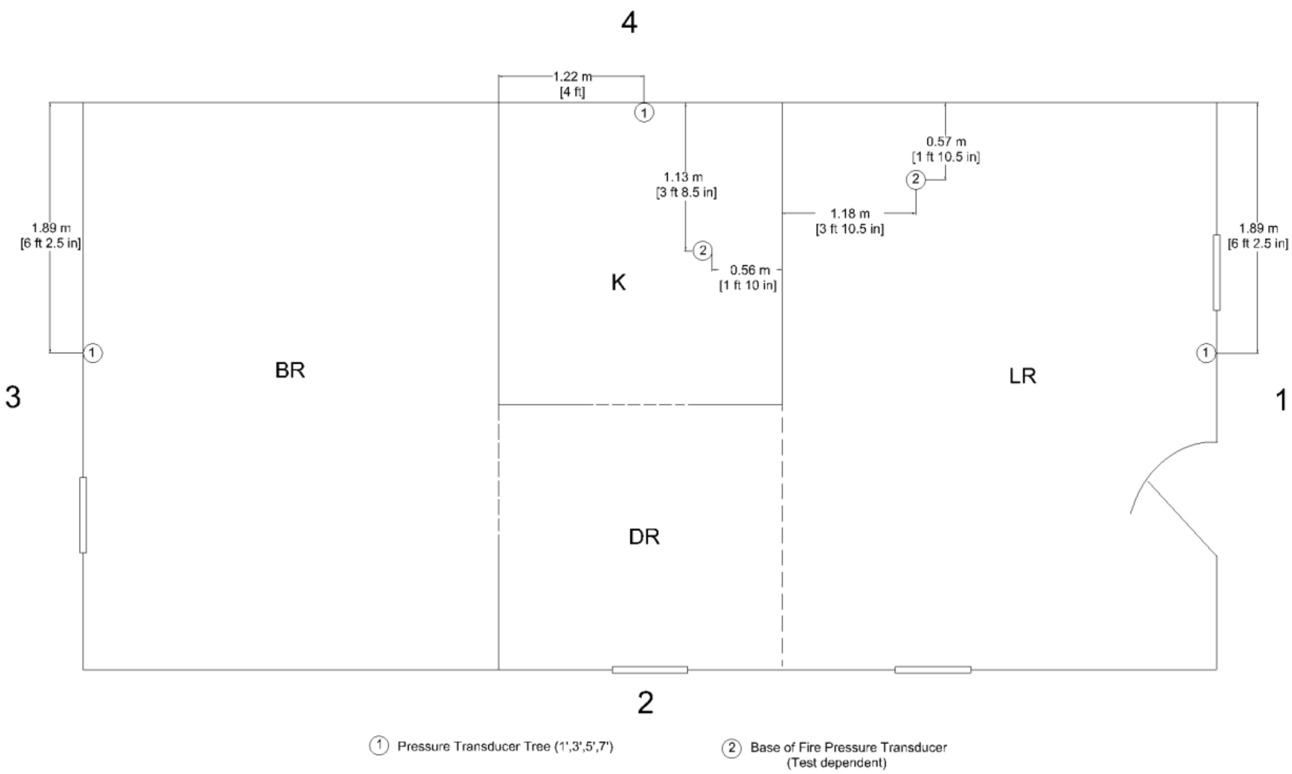


Figure 4-6. Pressure Transducer Locations

Four velocity probes were located in the opening between the DR and BR, 1.37 m (4 ft 6 in) from Wall 2. These four probes were at elevations of 0.51 m (1 ft 8 in), 1.02 m (3 ft 4 in), 1.52 m (5 ft), and 2.01 m (6 ft 7 in) as seen in Figure 4-7. An additional velocity probe was located in the bedroom window during ventilated conditions, 1.26 m (4 ft 1.5 in) from Wall 2. The elevation of this probe was 1.35 m (4 ft 5 in) during full open window ventilation, and 1.24 m (4 ft 1 in) during half open window and no window ventilation (see Figure 4-8).


Figure 4-7. BR door velocity probes


Figure 4-8. Window vent velocity probe

4.5 Gas Sampling Analyzers

Gas sampling analyzers were used to determine the amount of CO, CO_2 and oxygen present in the enclosure. For this test series, two types of analyzers were used which had two different ranges: Servomex 4100 analyzers and Siemens Oxymat 61/Ultramat 23 pairs. All samples were conditioned using a soot filter, a cold trap and a Drierite desicator. The locations and elevations of sampling probes varied between test scenarios.

Table 4-2 shows a detailed overview of what sampling probes were used during tests and what ranges were used for the sampling probes. The Servomex analyzers are referred to as the “Low” range and the Siemens analyzers are referred to as “High” range. Locations of the sampling probes can also be seen in Figure 4-9.

Table 4-2. Gas Sampling Probe Elevations and Tests Used

Probe Location	Elevation	Range	Tests Used
LR	0.61 m (2 ft)	Low	All
LR	1.52 m (5 ft)	High	All
LR	2.41 m (7 ft 11 in)	High	All
LR - Base of Fire	0.20 m (8 in)	Low	Sofa
DR	1.52 m (5 ft)	Low	Sofa
BR	0.61 m (2 ft)	Low	All
BR	1.52 m (5 ft)	Cabinet Tests - Low Sofa Tests - High	All
BR	2.41 m (7 ft 11 in)	High	All
K- Base of Fire	Low Cabinets - 0.41 m (1 ft 4 in) High Cabinets - 1.52 m (5 ft)	Low	Cabinets
K	2.41 m (7 ft 11 in)	High	Cabinets

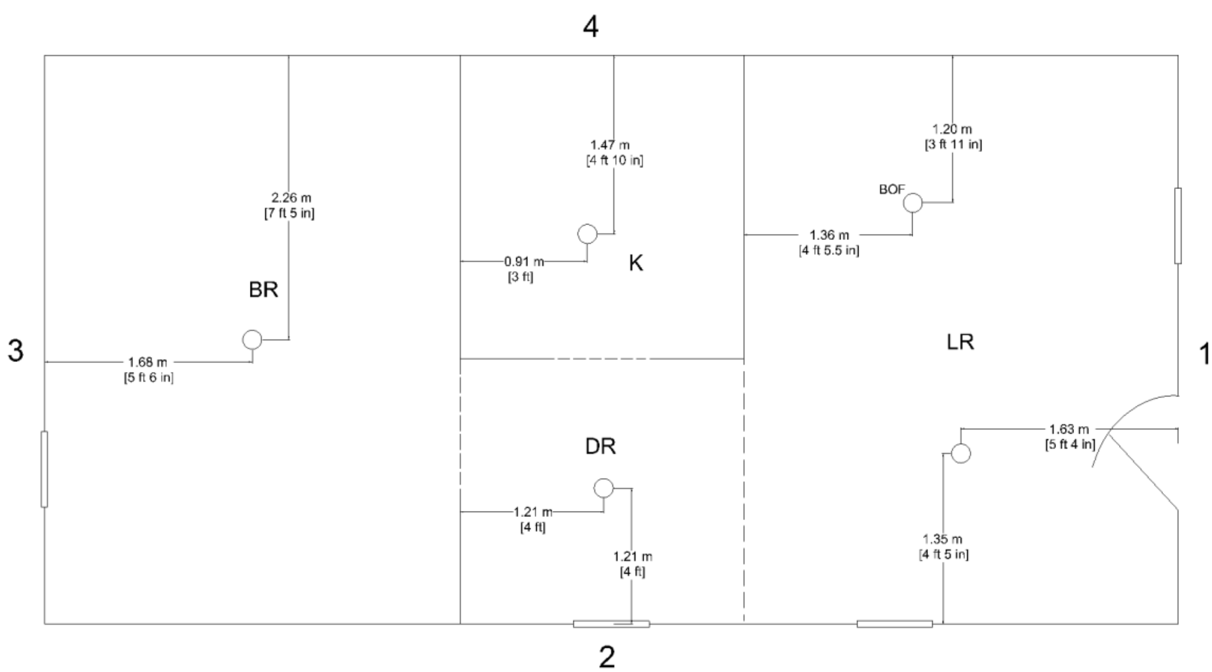


Figure 4-9. Gas Sampling Probe Locations

4.5.1 Servomex Analyzers

Four Servomex 4100 analyzers were used. The O_2 mole fraction was measured using a paramagnetic oxygen purity sensor contained within each of the analyzers. These sensors were operated in the range of 0 % to 22 %. Non-dispersive infrared (NDIR) gas sensors measured the CO and CO_2 mole fractions present in the gas samples. These analyzers had a range of 0 % to 1 % and 0 % to 10 % for CO and CO_2 concentrations, respectively. All three gas sensors were zeroed with 100% nitrogen. The CO/CO_2 sensors were calibrated with a 0.799% CO, 7.99% CO_2 mixture, with nitrogen balance. The O_2 sensors were calibrated with ambient air using a value of 20.95.

4.5.2 Siemens Analyzers

The Siemens analyzers were used in locations where CO/CO_2 levels were predicted to be higher than could be analyzed by the ranges of the Servomex analyzers. Each gas sampling line that used the Siemens analyzers was split into two and then analyzed by both an Oxymat 61 and an Ultramat 23.

4.5.2.1 Oxymat 61

The O_2 mole fraction was measured using a paramagnetic oxygen purity sensor contained within each of the analyzers. These sensors were operated in the range of 0 % to 22 %. The analyzers were zeroed using a 100% nitrogen gas and were calibrated with ambient air using a value of 20.95.

4.5.2.2 Ultramat 23

Non-dispersive infrared gas sensors measured the CO and CO_2 mole fractions present in the gas samples. These analyzers were operated at ranges of 0 % to 10 % and 0 % to 25 % for CO and CO_2 concentrations, respectively. The analyzers were zeroed using a 100% nitrogen gas. Calibration was performed with 8.9% CO, 18.9% CO_2 mixture, with nitrogen balance.

4.6 Optical Density Meters

Optical Density Meters (ODMs) were used to measure smoke obscuration within the enclosure. The ODMs consisted of a General Electric 6V light source directed at a Huygen Model 856 RRV Photocell. The path length for each ODM was1.52 m (5 ft). The ODMs were constructed in general accordance with the requirements of UL 217 (UL 217, 2006).

ODMs were placed in the BR, LR and DR. In the LR and DR, an ODM was present at elevations of 0.61 m (2 ft), 1.52 m (5 ft), and two at 2.44 m (8 ft). One ODM was located in the DR at an elevation of 2.44 m (8 ft). Locations of these ODMs can be seen in Figure 4-10.

Prior to the beginning of the test series, the ODMs were calibrated using Melles-Griot neutral density filters. The filters used were 0.1, 0.316, 0.501, 0.794 and 0.933 obscuration.

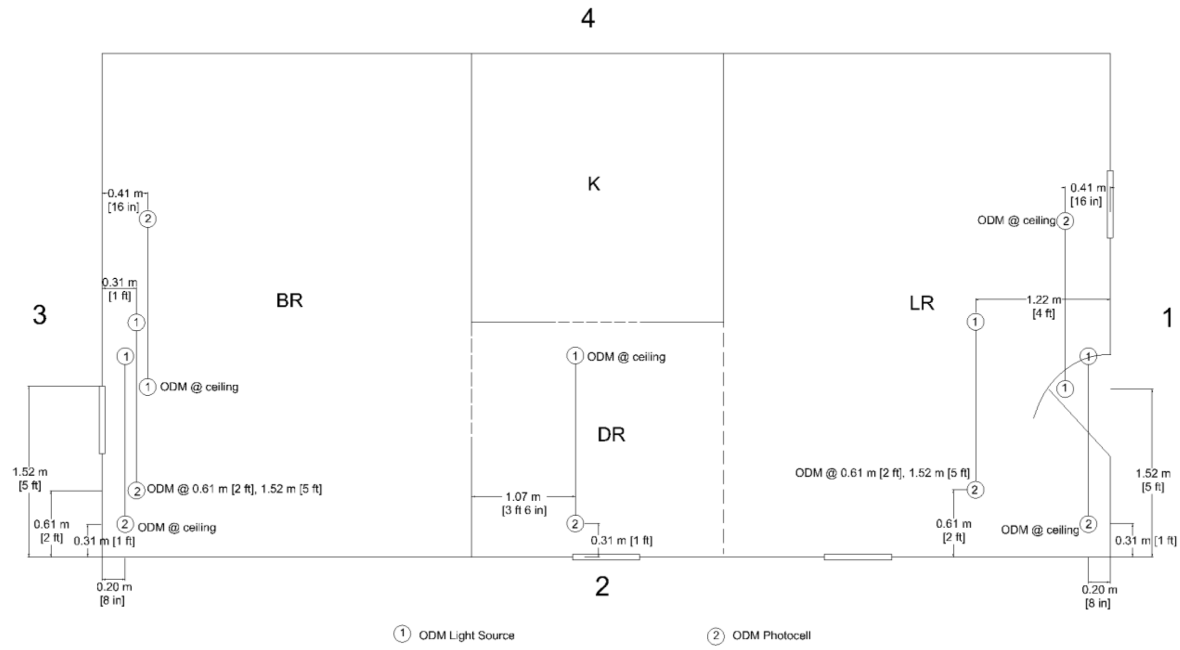


Figure 4-10. ODM locations

4.7 Load Cell

During the experiments, mass loss of the fuel was recorded using a platform scale (Sterling Scale, Model 810-N4). The scale had a maximum capacity of 453.6 kg (1000 lb) with 0.05 kg (0.1 lb) resolution. The load cell was fitted with a specially designed frame that was positioned on top of the load cell and extended into the enclosure (see Figure 4-11, Figure 4-12). The bottom frame that rested on the load cell and the top frame, which supported the fuel load, were constructed of 0.04 m ($1^{5}/_{8}$ in) by 0.08 m (3 in) slotted steel channel. The two frames were supported by four 0.71 m (28 in) sections of 0.03 m (1 in) black pipe. Four 0.05 m (2 in) diameter holes were drilled in the enclosure floor to allow the frame to pass through. The top frame was elevated 0.05 m (2 in) off of the enclosure floor and had two sheets of 0.013 m (0.5 in) GWB on top of it. The total height of the load cell frame from the enclosure floor was 0.2 m (8 in). Figure 4-13 shows a side view of the load cell frame. The top of the frame measured 2.13 m (7 ft) by 1.22 m (4 ft).

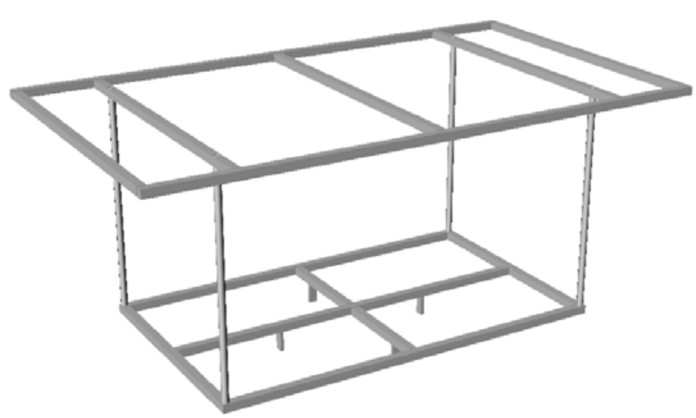


Figure 4-11. Mass loss frame

Figure 4-12. Mass loss frame in place during burner test

Figure 4-13. Side view of load cell frame inside enclosure

The scale was always located under the enclosure, however, the scale position changed depending on the test. For sofa tests, the load cell was positioned so that one edge of the top of the frame was 0.20 m (8 in) from Wall 4 and another edge was 0.10 m (4 in) from Wall A in the LR. For cabinet tests, the load cell was positioned so that the top frame was centered between Walls A and C in the kitchen, with the back edge 0.10 (4 in) from Wall 4.

4.8 Data Acquisition

Data acquisition was achieved using the ATF FRL existing system. Control of the acquisition was achieved using iFix Intellution, a Supervisory Control and Data Acquisition system (SCADA). The data collection and cataloging was performed through FireTOSS, a software package unique to the ATF FRL. Instrumentation was connected to the SCADA through Yokogawa DA 100 and DS 600 data acquisition units. A sampling frequency of 1 Hz was used for all tests.

4.9 Soot Deposition Targets

To characterize soot deposition during each test, four painted GWB targets were placed within the enclosure, one in each room. The targets were 0.61 m (2 ft) wide x 2.44 m (8 ft) high sheets of 0.012 m (0.5 in) GWB, painted with the same paint as the interior walls. In addition, two 0.31 m x 0.31 m carpet sample were placed in the enclosure, one in the living room and one in the bedroom. Figure 4-14 shows the locations of each target.

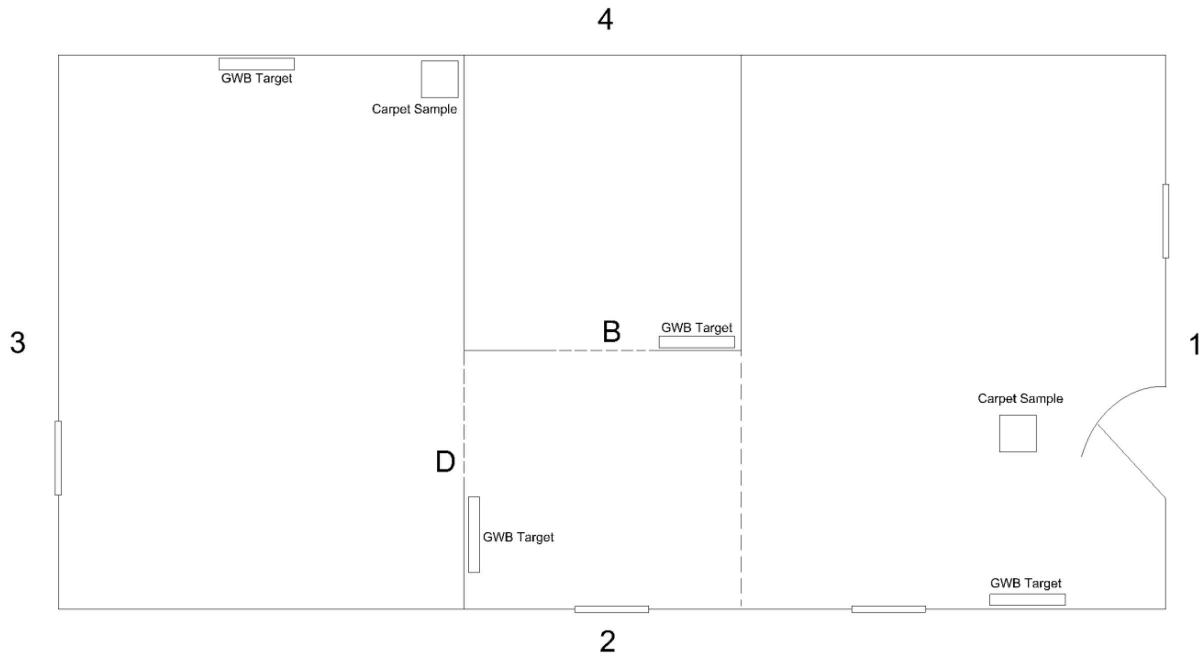


Figure 4-14. Target and carpet sample placement in enclosure

4.10 Video

The events of each test were documented using video cameras. A total of five video cameras were used. Video cameras were located at viewports (see Section 3.2.2) or directed at vent openings. Video cameras at viewports were stopped when there was no visibility due to black smoke obscuration.

In addition to standard video cameras. IR cameras were also used. For the sofa tests, a Bullard IR camera was positioned directly under the viewport closest to the door on Wall 1. The camera was inside the enclosure. For the cabinet tests, a FLIR, ThermaCAM P640 was used for IR video data. The camera was located on the outside of the enclosure, directly beneath the DR window. The FLIR camera used a Zinc Selenide viewport. This type of viewport was used because it transmits well at the wavelengths used by the FLIR camera. The FLIR camera was operated in the 25°-500°C (77°-932°F) range.

4.11 Photos

Photos were taken of the enclosure before, during and after each test. The pictures during the test were mainly to document the events that occurred during the test. The main purpose of the before and after photos was to help with the forensic analysis that is presented later. Smoke layer heights, burn patterns, and fuel consumption were some of the major documentation points. In addition, these photos were helpful in documenting fuel load locations and overall conditions of the enclosure. All photos were uploaded and synched to the data acquisition time of FireTOSS.

4.12 Instrumentation Calibration and Diagnostics

Prior to each test, the instrumentation was calibrated and/or checked for functionality. Thermocouples were checked for functionality by exposing a small flame from a butane lighter to the bead. The reading was then checked in iFix. If the thermocouple displayed a temperature rise, it was determined to be operational.

For pressure and heat flux transducers, a two minute background data collection was run before each fire test. The values from this background collection were input into the data acquisition system and used as the ambient values for the respective instrument.

The load cell with the platform was zeroed before each test, before the fuel load was installed. This ensured that the mass loss measured would only be from the fuel.

The gas analyzer and transport delay times for the gas sampling systems was determined using a bladder filled with the calibration span gas. The analyzers were calibrated and then allowed to run at ambient conditions for at least two minutes. The bladder was attached to the sample port being tested via a three-way valve. The time delay from when the span gas was released into the sample line until the analyzer read 90% of the span gas concentration was determined to be the analyzer sampling delay time. Table 4-3 contains these delay times. This time delay calculation was done prior to the beginning of the test series. In addition, the analyzers were calibrated before each test, and then allowed to run at ambient for at least two minutes.

Table 4-3. Gas Sampling Delay Times

Location of Sampling Port	Analyzer Range	Delay Time (s)		
		CO	CO_2	O_2
LR 0.61 m (2 ft)	Low	18	25	26
LR 1.52 m (5 ft)	High	19	24	21
LR 2.41 m (7 ft 11 in)	High	17	23	19
BR 0.61 m (2 ft)	Low	30	29	28
BR 1.52 m (5 ft) (Sofa Tests), K 2.41 m (7 ft 11 in) (Cabinet Tests)	High	17	16	19
BR 2.41 m (7 ft 11 in)	High	17	23	21
DR 1.52 m (5 ft) (Sofa Tests), BR 1.52 m (5 ft) (Cabinet Tests)	Low	37	37	31
Base of Fire	Low	51	50	29

5 TEST PROCEDURES AND GENERAL RESULTS

This section details the procedures for each test performed, as well as general results and data for each test. The data presented here are temperature and gas concentrations in the room of origin, as well as the heat release rate (HRR) of the fuel source, as calculated from the in-situ fuel mass loss measurement and the heat of combustion determined in the calorimetry tests. Other data is addressed in Section 0. All data is presented from the time of ignition of the flaming tests or from heater initiation in the smoldering tests. The data is not shifted to account for tissue box ignition times, as the tissue box ignition scenario was determined to be generally repeatable within 20 seconds.

5.1 Calorimetry Tests

Calorimetry of the sofa and cabinet fuel loads was performed under a 1 MW hood calorimeter in the ATF FRL Medium Burn Room. These tests were designed to examine the burning characteristics of the fuel loads, such as heat release rate and smoke production. The calorimetry tests were designed so that the fuel load orientation and ignition scenario were identical to that of the compartment fire tests.

For test CAL1, the sofa was placed on two sheets of 0.012 m (0.5 in) GWB, which was placed on top of the load cell (no frame). The ignition scenario used was the accidental flaming ignition scenario. Figure 5-1 shows the calorimetry setup. The sofa was ignited and allowed to burn to complete consumption. This test was performed twice to assess repeatability of results.

Figure 5-1. Test CAL1 setup

For tests CAL2, the array of four cabinets were hung on a 2.44 m (8 ft) by 1.22 m (4 ft) wall that had the same construction as the interior walls of the enclosure (see Figure 5-2). The assembly was placed on top of the load cell. The two leftmost cabinets were loaded as described in Section 3.4.2. The ignition was performed using the accidental flaming ignition scenario. The cabinets were allowed to burn to complete consumption. This test was performed twice.

Figure 5-2. Test CAL2 setup

The heat release rate of each setup was calculated by FireTOSS for each test using the oxygen consumption data recorded by the calorimeter. These heat release rates are displayed in Figure 5-3 and Figure 5-4. The average mass loss rate was determined by first taking a 30 second running average of the mass measurement, and then calculating an instantaneous slope for each time step. This calculated slope yielded the mass loss rate as a function of time. The instantaneous heat release rate was then divided by the instantaneous mass loss rate to yield a heat of combustion value at each time step. These values were then averaged over a specified time period to yield an effective heat of combustion for each test. The sofa data was averaged over the period of time between when the sofa was first involved (i.e., when the HRR started to rise) to the time when the majority of the polyurethane had been consumed and only the wood frame remained. For the cabinets, the data was averaged from ignition of the first cabinet to the end of the test. The two calorimetry tests for each source were then averaged together for an effective heat of combustion for that particular fuel source. The data for these calculations is displayed in Table 5-1.

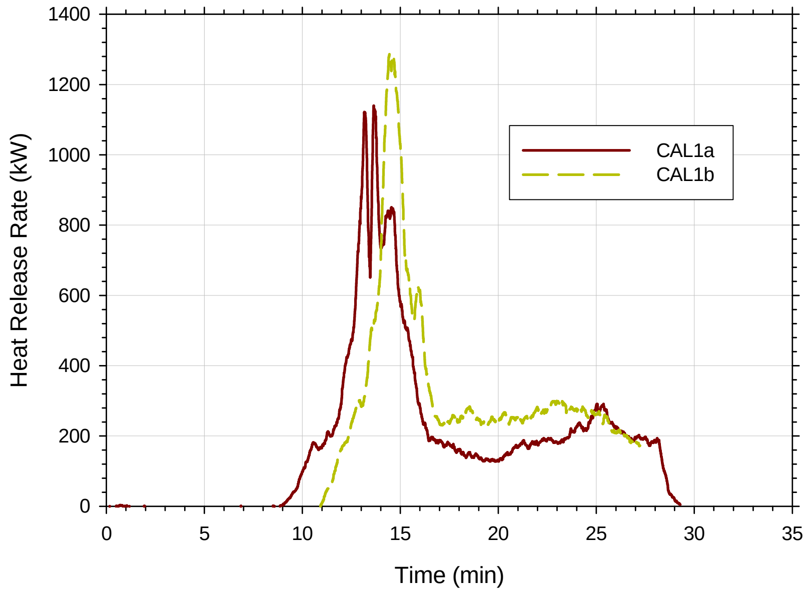


Figure 5-3. Sofa heat release rates for test CAL1

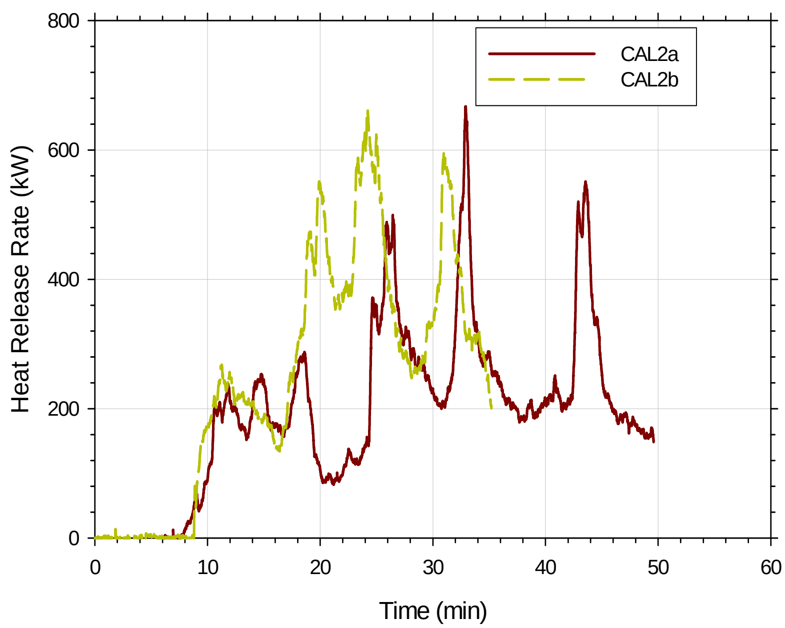


Figure 5-4. Cabinet array heat release rates for test CAL2

Table 5-1. Calculated Heat of Combustion Values (MJ/kg) from Calorimetry Tests

Test	Fuel Source	Calculated Heat of Combustion	Fuel Source Average Heat of Combustion
CAL1a	Sofa	13.1	14.0
CAL1b	Sofa	14.8	
CAL2a	Cabinets	13.5	12.3
CAL2b	Cabinets	11.1	

The measured heat of combustion for the cabinets is in close agreement with the literature value for oak of 12.4 MJ/kg (Tewarson, 2002).The value for the sofa is less than the published values of 16.4-19 MJ/kg for polyurethane (Tewarson, 2002).However, an upholstered furniture item used in the CBUF testing, designated Sample 2:13, had very similar makeup to the sofa that was used in this test series. The furniture item in the CBUF testing had CMHR urethane filling with polyester wadding and a 100% cotton fire resistant covering (Sundström, 1995). The heat of combustion value that was determined for the CBUF furniture was 14.33 MJ/kg; this agrees well with the value of 14 MJ/kg calculated for the sofas in this test program.

Another different, but explainable, heat of combustion for a sofa is the value of 19.7MJ/kg as calculated using the same sofa in a previous study (Mealy & Gottuk, 2006). Both measurements and calculation methods were done in the same manner. Support of the lower value in this test program can be found by comparing the CO/CO_2 ratios from these tests and that in the previous test by Mealy and Gottuk. As Figure 5-5 shows, tests CAL1a and CAL1b had much higher CO/CO_2 ratios than the test by Mealy and Gottuk. This demonstrates that the previous test by Mealy had more efficient combustion and would thus yield a higher heat of combustion value.

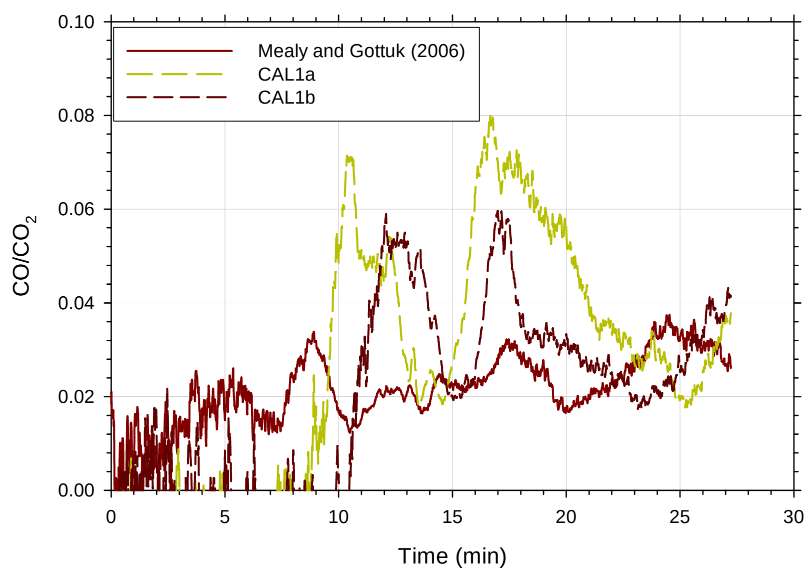


Figure 5-5. CO/CO_2 ratio comparison of sofa calorimetry tests

5.2 Enclosure Leakage Characterization

Leakage rates for the entire test enclosure were characterized using a Retrotec, Model E53C, blower door-fan system. The door-fan was installed within the exterior doorway prior to any tests being conducted within the enclosure. The system monitored pressure differentials between the lab environment and that within the enclosure, under non-fire conditions. Based upon these differentials an estimated leakage area (ELA) for the entire enclosure was calculated. An average estimated leakage area for the enclosure was 0.015 m^2 (0.16 ft^2).

5.3 Controlled Fire Tests

Burner tests were performed inside the enclosure to check the operation of instrumentation and to determine baseline fire behavior inside the enclosure for a well-characterized source. The fire in these tests was provided by a 0.41 m (16 in) by 0.41 m (16 in) sand burner with natural gas fuel. The fire size was 125 kW and was controlled by an Alicat Scientific Model MCR-1000S2PM-D mass flow controller that was in-line with the natural gas supply line. The uncertainty of the flow controller was ± 0.8% of the reading. Ignition of the burner was achieved by a propane pilot flame. The pilot was ignited with the natural gas mass flow controller secured. After the pilot was ignited and the compartment sealed, the mass flow controller was turned on and the 125 kW flame was verified. The burner was placed in the LR where the sofa would be placed during fire tests (see Figure 5-6). The burner was turned off after 10 minutes, and the test was ended 2 minutes later, for a total duration of 12 minutes. Two burner tests were performed. One test (B1) was performed with no ventilation, the other with full open window ventilation (test B2).

Figure 5-6. Burner placement for tests B1 and B2

5.3.1 Test B1 Results – No Ventilation

Figure 5-7 and Figure 5-8 display temperature and oxygen concentration data for test B1. A peak room of origin ceiling temperature of 244°C was reached during the test. The oxygen concentration reached a minimum value of 14.2% at ceiling height in the enclosure.

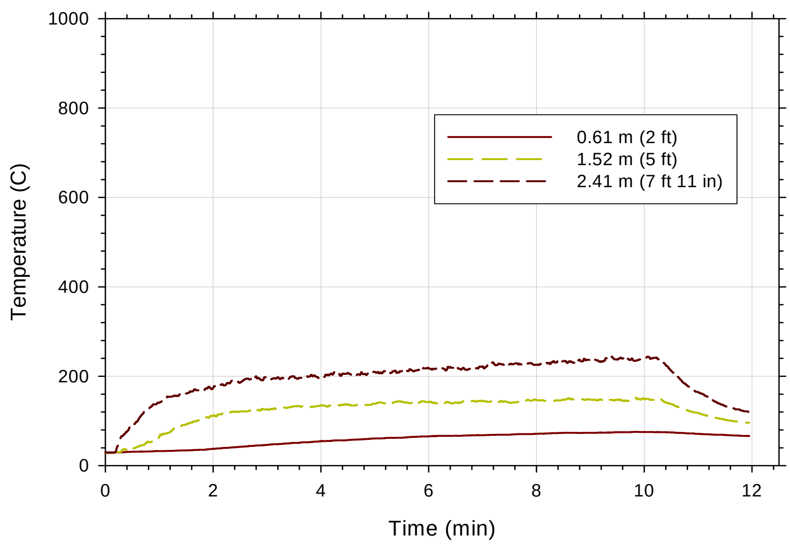


Figure 5-7. Room of origin temperature data for test B1 with a 125 kW natural gas fire and no ventilation

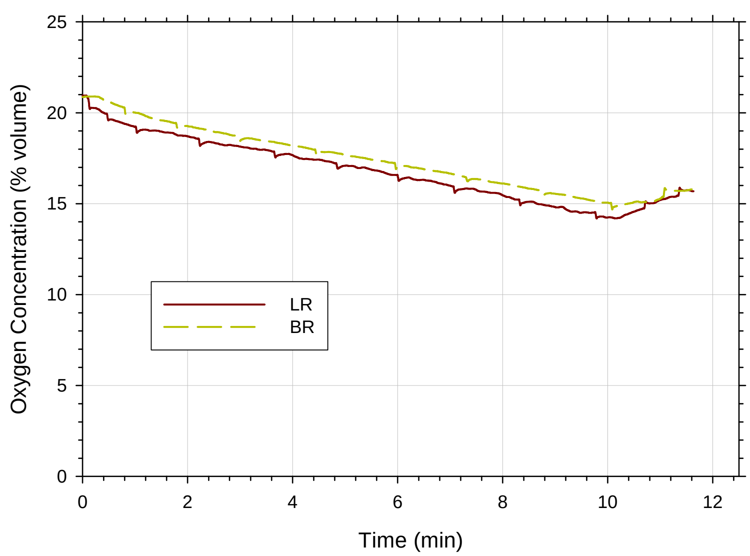


Figure 5-8. Oxygen concentration data for test B1 with a 125 kW natural gas fire and no ventilation

5.3.2 Test B2 Results - Full Open Window Ventilation

Figure 5-9 and Figure 5-10 display basic temperature and oxygen concentration data for test B2. A peak room of origin ceiling temperature of 242°C was reached. The oxygen concentration reached a minimum value of 15.1% at ceiling height in the enclosure.

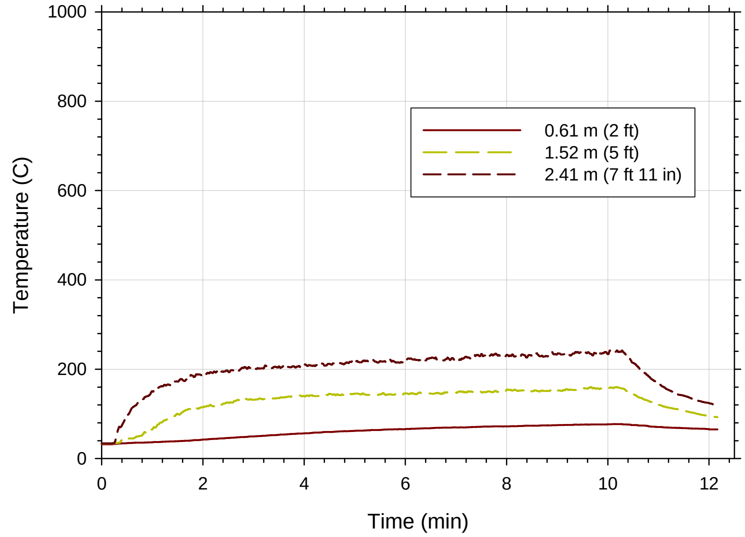


Figure 5-9. Room of origin temperature data for test B2 with a 125 kW natural gas fire and a full open window

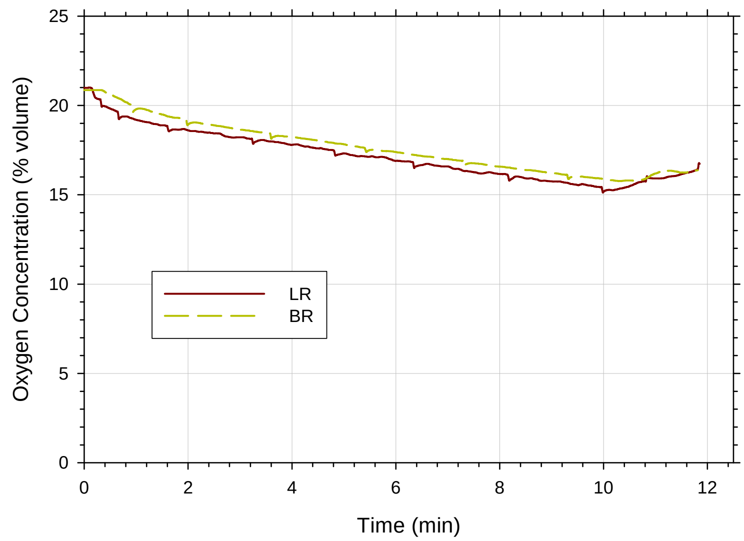


Figure 5-10. Oxygen concentration data for test B2 with a 125 kW natural gas fire and a full open window

5.4 Smoldering Tests

5.4.1 SM1 – Smoldering Batting

This test was designed to simulate a smoldering bedding fire. This test used the smoldering ignition scenario and no ventilation. The cotton batting described in Section 3.4.3 was positioned on top of a 0.012 m (0.5 in) sheet of GWB which was placed on top of a Sartorius Series FB scale with a 16 kg capacity and a 0.1 g resolution (see Figure 5-11). A different scale was used in this test for better resolution, since the batting weighed significantly less than the sofa or cabinets, and the smoldering scenario would yield a slower mass loss rate than a flaming scenario. The cartridge heater was placed between folds 21 and 22 of the batting, approximately 0.06 m (2.1 in) from the base of the batting, near the center of the layer (see Figure 5-12). The test was started with the compartment completely closed. The power source for the cartridge heater was wired outside of the enclosure. The cartridge heater was turned on for 20 minutes, and then turned off to allow the batting to self smolder. Visible smoke could be seen coming from the source approximately 5.7 minutes after the heater was turned on and visible charring was observed after approximately 8 minutes. Smoldering continued after the heater was turned off. The test was allowed to run until the gas levels inside the enclosure began to return to ambient, a duration of 220 minutes.

Figure 5-11. Test SM1 setup

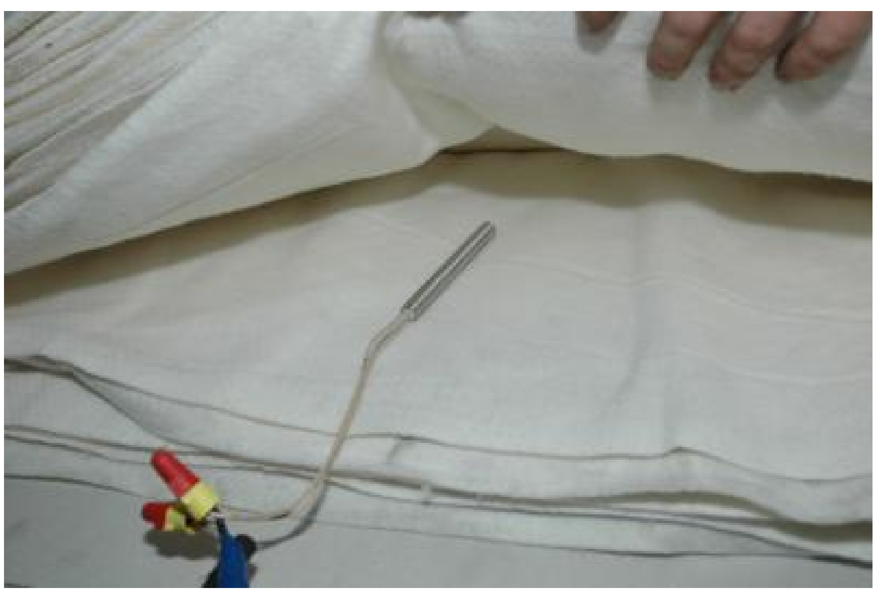


Figure 5-12. Cartridge heater position during test SM1

The temperatures in this test did not rise above 40°C. The oxygen concentrations did not fall below 19.9% within the enclosure. CO concentrations reached a maximum of 0.29% and CO_2 reached a maximum concentration of 1.0%. The total mass loss of the cotton batting was 4.2 kg, approximately 85% of the total mass.

5.4.2 SM2 – Smoldering Sofa 1

This test was designed to simulate a smoldering sofa fire. This test used the smoldering ignition scenario and no ventilation. The sofa was positioned on the load cell setup in the LR (see Figure 5-13). A small hole, approximately 0.01 m (0.4 in) in diameter, was cut in the center of the sofa. The position of the cut was 0.25 m (10 in) from the back of the seat and 0.70 m (2 ft 3.5 in) from either armrest. The size of the hole was chosen because it was slightly smaller than the diameter of the cartridge heater. The cartridge heater was placed in the hole, as seen in Figure 5-14. The door and windows were all closed prior to beginning the test. The cartridge heater power source was located outside of the enclosure. To initiate the test, the cartridge heater was powered on, and then left on for 20 minutes. Visible smoke could be seen coming from the sofa approximately 2.8 minutes after the heater had been turned on. After the initial 20 minutes, the power was turned off to allow the sofa to self smolder. However, smoldering did not continue. After seven minutes from turning it off, the cartridge heater was powered back on for the remainder of the test. The test was allowed to continue until visible smoke production had ceased, a duration of 89 minutes.

Figure 5-13. Test SM2 setup

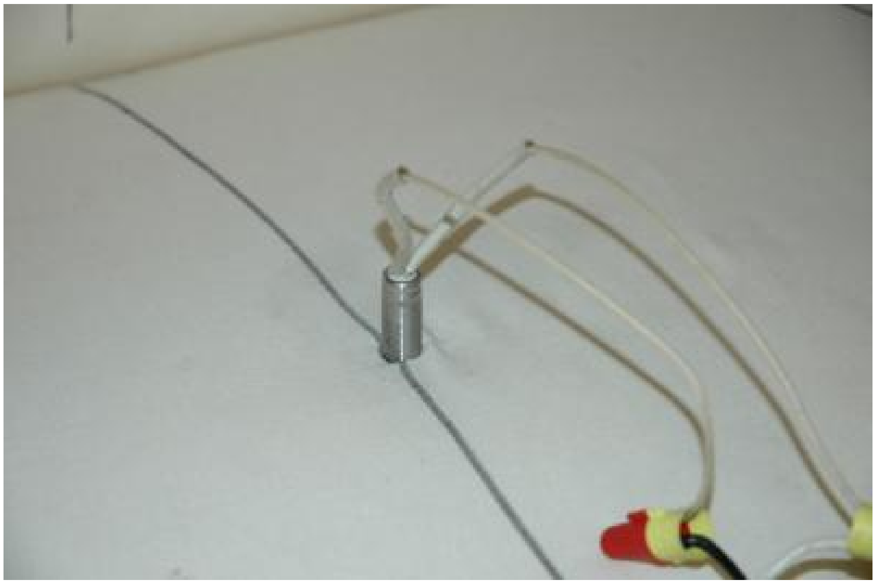


Figure 5-14. Test SM2 cartridge heater close-up

The temperatures in this test did not rise above 28°C. During the test, there was no measurable change in any gas concentration. In addition, there was no measurable mass loss. A 0.20 m (8 in) diameter area of fabric and foam surrounding the cartridge heater was charred, however no material was completely consumed (see Figure 5-15 to Figure 5-18).

5.4.3 SM3 – Smoldering Sofa 2

Similar to test SM2, test SM3 was designed to simulate a smoldering sofa fire. This test used the smoldering ignition scenario and no ventilation. The sofa was placed on the load cell setup in the living room (see Figure 5-15). In this test, two cartridge heaters were used, positioned in 0.01 m (0.4 in) diameter holes located 0.25 m (10 in) from the back of the seat and 0.25 m (10 in) from either armrest. The cartridge heaters were tied to the ceiling in this test to prevent the heaters from dropping through the sofa as the foam pyrolized. Two cartridge heaters were used to attempt to get a larger portion of the sofa involved in the smoldering process then had occurred in SM2. The door and windows were all closed prior to beginning the test. The cartridge heater power source was located outside of the enclosure. To initiate the test, both cartridge heaters were powered on. The cartridge heaters were left on for the duration of the test to ensure continued smoldering. Visible smoke was observed coming from the sofa after approximately 3 minutes. The test was allowed to continue until visible smoke production ceased, a duration of 126 minutes.

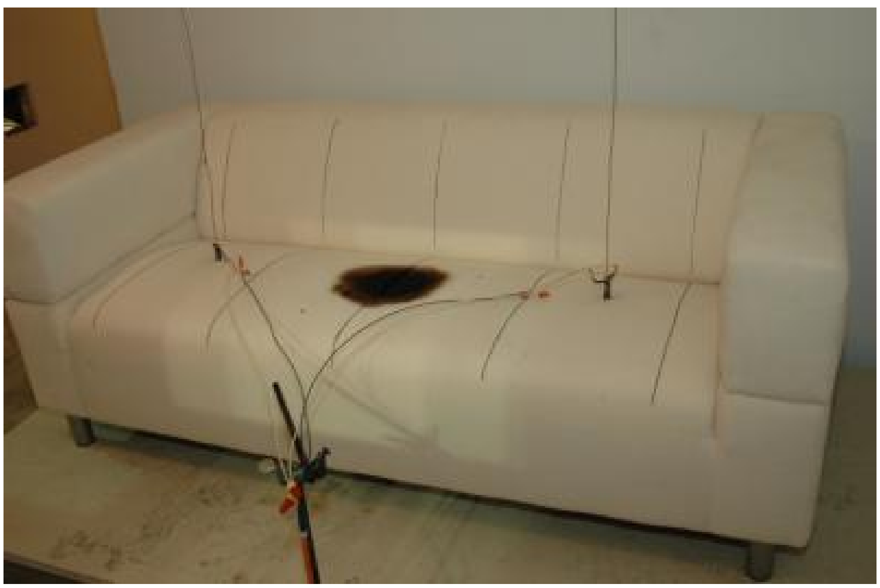


Figure 5-15. Test SM3 setup with damage from SM2 in the center.

The temperatures in this test did not rise above 29 °C. During the test, there was no measurable change in any gas concentration. In addition, there was no measurable mass loss. An approximately 0.24 m (9.5 in) diameter area surrounding each of the cartridge heaters sustained charring to the cover and foam (see Figure 5-16, Figure 5-17). None of the material was completely consumed.

Figure 5-16. Test SM3 damage (the center char area is from test SM2)

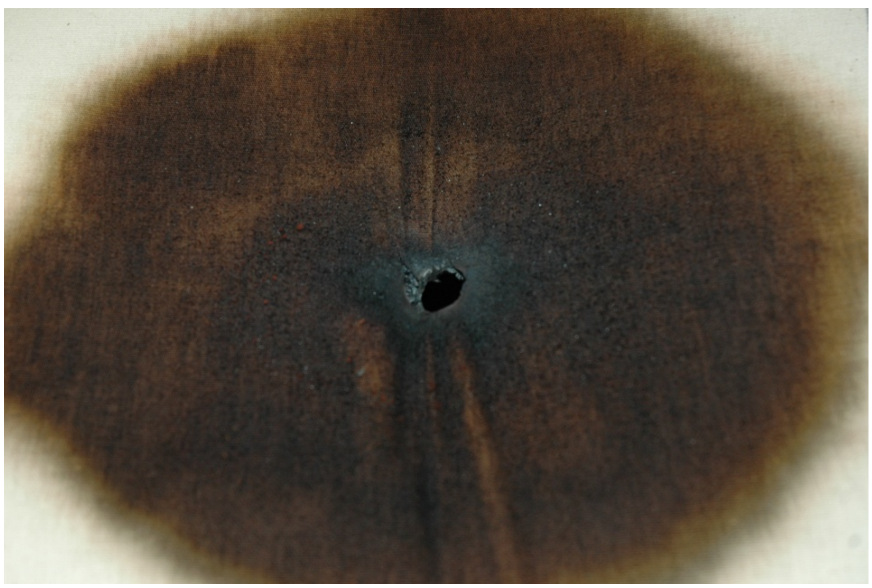


Figure 5-17. Close-up view of the damage caused in tests SM2 and SM3

Figure 5-18. Close-up view of damage to underside of sofa seat caused in SM2, SM3

5.4.4 SM4 – Smoldering Sofa 3

This test was designed to simulate a longer self-sustaining smoldering sofa fire than was achievable in SM2 and SM3. This test used no ventilation. The sofa used in this experiment was different than the sofa used for all other sofa tests (see Figure 5-19). The sofa, purchased at a thrift store, had three polyurethane foam seat cushions with 100% cotton coverings and a wood frame. The sofa was of similar size to the IKEA sofa used in the other tests. The cartridge heater was placed on a 0.20 m (8 in) by 0.31 m (1 ft) piece of the same cotton batting used in test SM1. The batting was used to initiate the smoldering process. This setup was then positioned between the middle seat cushion and the sofa back, as seen in Figure 5-20. (Note: this same setup was attempted multiple times on an IKEA sofa and failed to result in smolder.) The cartridge heater power source was located outside of the enclosure. To initiate the test, the cartridge heater was powered on, and then left on for 20 minutes. Visible smoke was observed coming from the sofa after approximately 4.5 minutes. After the initial 20 minutes, the power was turned off and the sofa was allowed to self smolder. Increased smoke production was observed after approximately 87 minutes. The test was allowed to continue for a duration of 117 minutes at which point the test was ended due to time constraints.

Figure 5-19. Sofa used for test SM4

Figure 5-20. Cartridge heater setup for test SM4

The temperatures in this test did not rise above 29°C. During the test, there was no measurable change in oxygen or CO_2 concentrations. CO concentrations reached a maximum of 0.075%. This test was run chronologically between two cabinet tests, and due to this, the load cell was installed in the kitchen. Therefore, the cushions were removed and weighted before and after the test using the scale from test SM1 to determine the total mass loss over the duration of the test. The original mass of the bottom seat cushions was 5.63 kg. The total mass loss was 1.09 kg, approximately 19% of the total mass. Mass lost from the attached seat cushions was not measurable; however, the mass lost appeared to be negligible compared to the mass lost from the bottom seat cushions (see Figure 5-21). Approximately half of the center cushion was completely consumed. Charring and some consumption of material were present on the sides of the outer cushions and back of the sofa.

Figure 5-21. Test SM4 damage

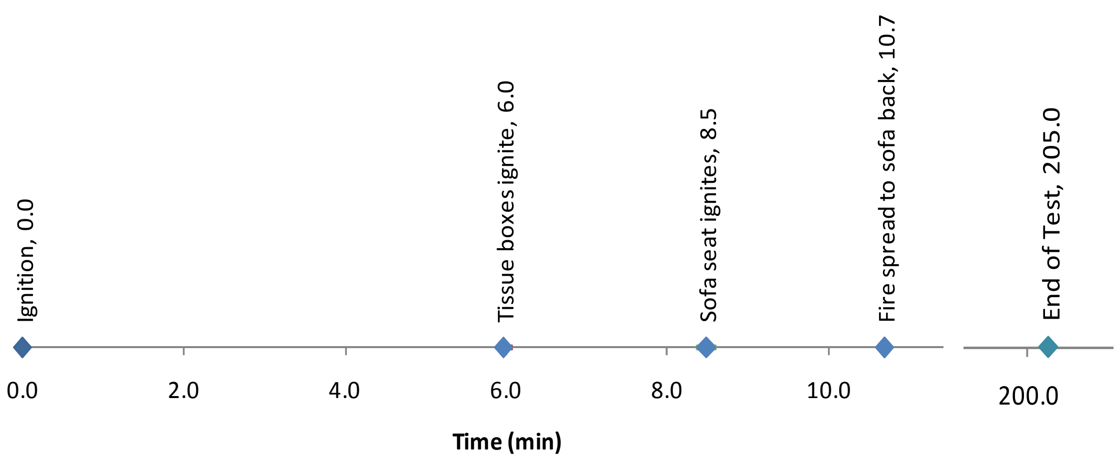
5.5 S1, S2, S3 – Non-accelerated Flaming Sofa Tests

These tests were designed to represent flaming sofa fires initiated by a small flaming source. These tests used the class A flaming ignition scenario. The sofa was placed on the load cell setup in the living room. The tissue boxes of the ignition scenario were positioned with the ends against the back of the sofa, and were centered between the two armrests. The cap of alcohol was positioned on the end of the tissue boxes furthest from the sofa back (see Figure 5-22). The armchair and coffee table were present within these tests, and positioned as described in Section 3.4.1.2. To initiate these tests, the alcohol was ignited using a butane lighter. After ignition, all personnel exited the enclosure and the door was closed. The only difference between the three non-accelerated flaming sofa tests was the ventilation schemes used. Test S1 had no ventilation, S2 had full open window ventilation, and S3 had half open window ventilation. Tests S1 and S3 were allowed to continue until conditions in the enclosure began to return to ambient. Test S2 was manually extinguished.

Figure 5-22. Setup for sofa accidental flaming tests

5.5.1 S1 Results – Sofa with No Ventilation

The duration of the test was 205 minutes. The following timeline gives a brief synopsis of the events that occurred during this test.

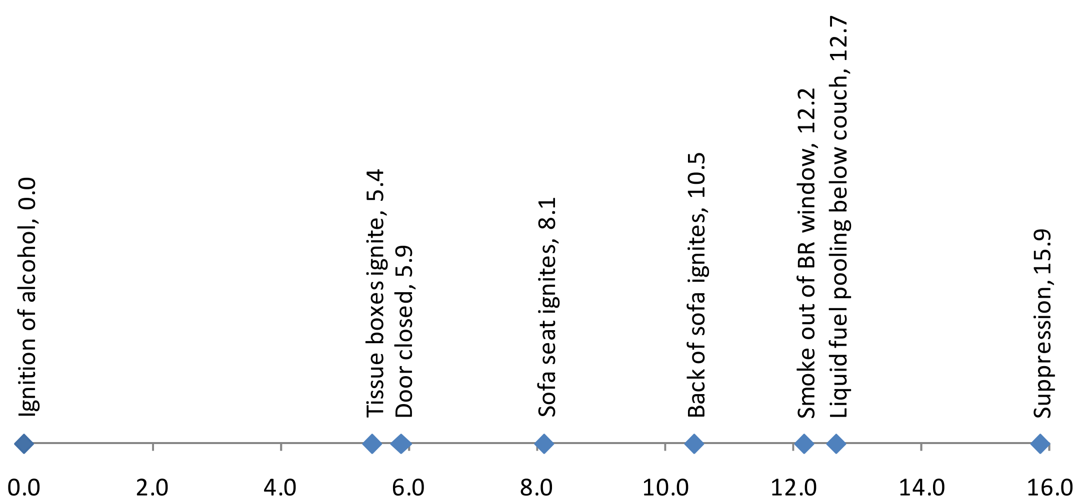


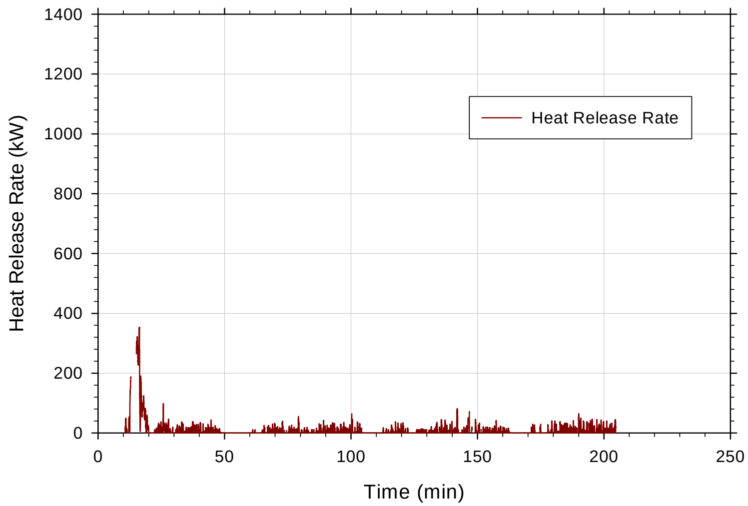
Data from this test is presented in Figure 5-24. The peak temperature reached during this test was 286°C in the living room. The oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 13.6%. The peak CO concentration was 0.4%. The peak CO_2 concentration was 4.5%. The initial mass of the sofa was 49.77 kg. During the test, the total mass loss was 5.80 kg, approximately 12% of the initial mass. The maximum heat release rate calculated during this test was 353 kW. The fire burned away a section of the seat and back approximately 3 ft wide. The remainder of the seat and back were heavily charred but still intact (see Figure 5-23).

Figure 5-23. Test S1 damage

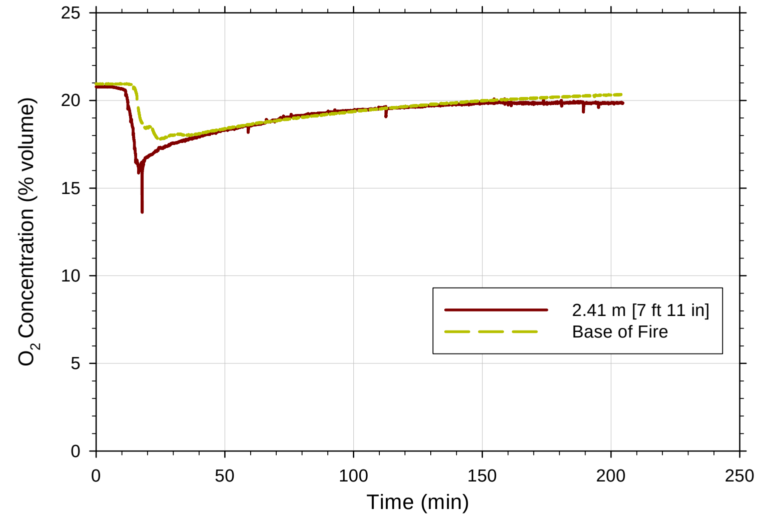
5.5.2 S2 Results – Sofa with Full Open Window

The duration of the test was 16 minutes. This test was prematurely manually extinguished because at the time there was a concern that the fire was approaching flashover and there was a concern to limit damage to the enclosure. The following timeline gives a brief synopsis of the events that occurred during this test.

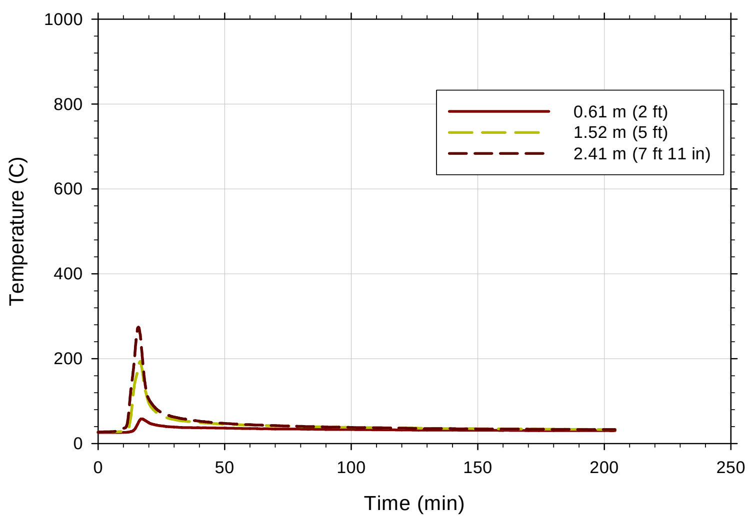




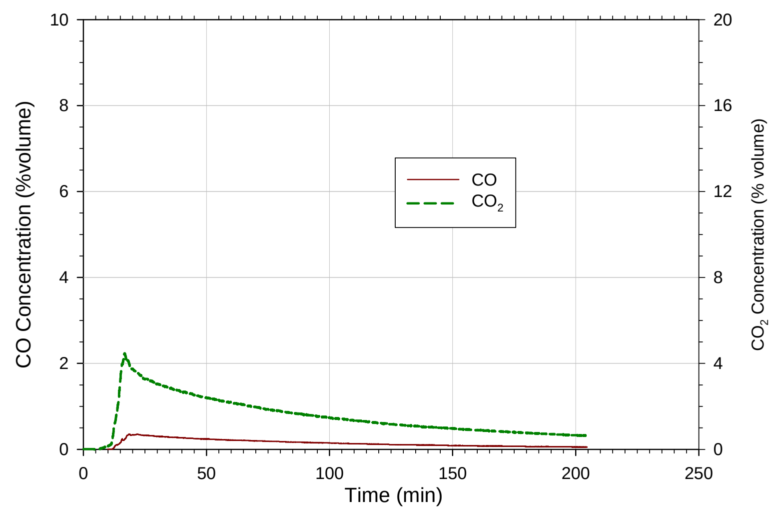
(a) Heat Release Rate



(b) Oxygen Concentrations in Room of Origin



(c) Temperature in Room of Origin



(d) Gas Concentrations at 2.41 m (7 ft 11 in) in Room of Origin

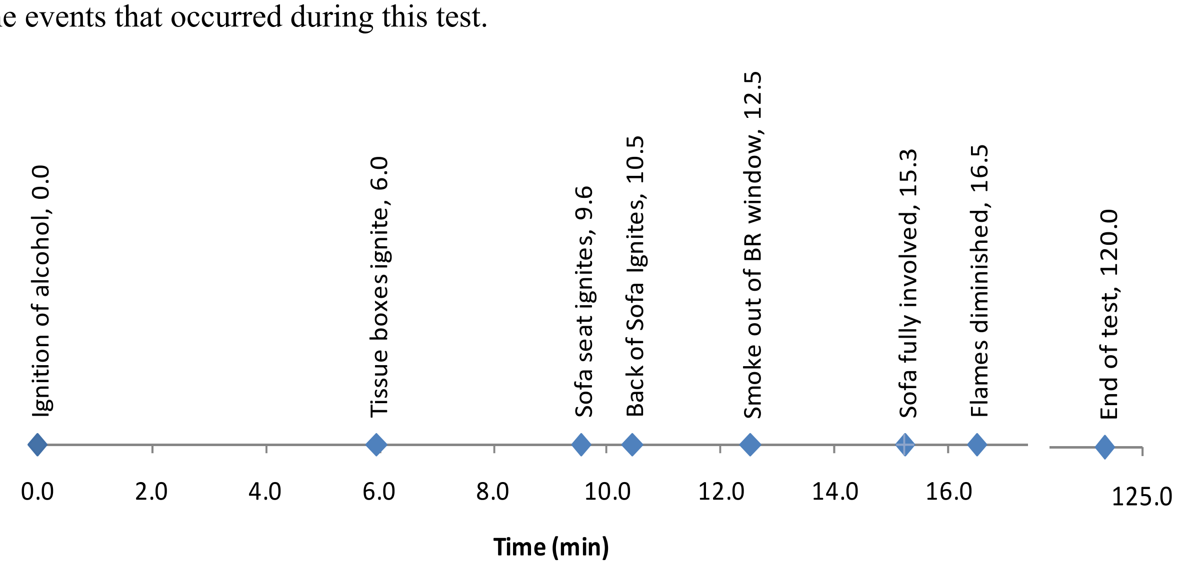
Figure 5-24. Test S1 Data – sofa with no ventilation

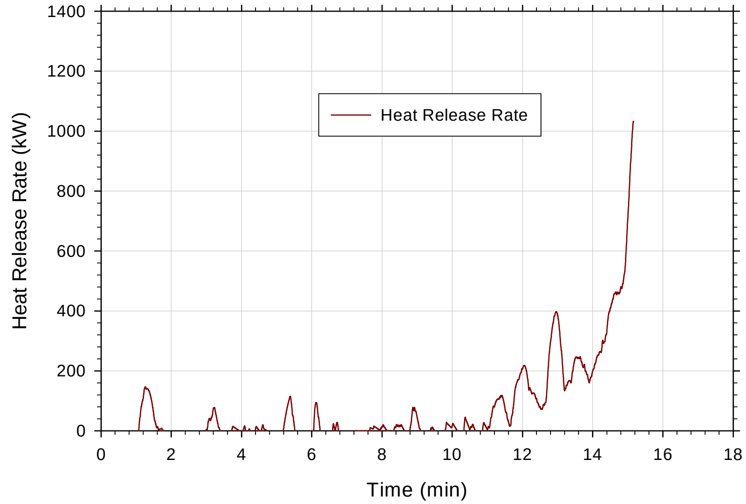
Data from this test is presented in Figure 5-26. Before suppression, the peak temperature reached during this test was 638°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 4.8%. The peak CO concentration was 3.7%. The peak CO_2 concentration was 12.9%. The initial mass of the sofa was 49.64 kg. During the test, the total mass loss was 5.1 kg, approximately 11% of the initial mass. The maximum heat release rate calculated during this test was 1.03 MW, which occurred just before suppression. The choice to suppress the fire was made due to rapidly increasing temperatures and flaming across the ceiling which was visible through the wall 1 window. A majority of the material was burned away on the sofa seat, back and interior of the armrests (see Figure 5-25).

Figure 5-25. Test S2 damage

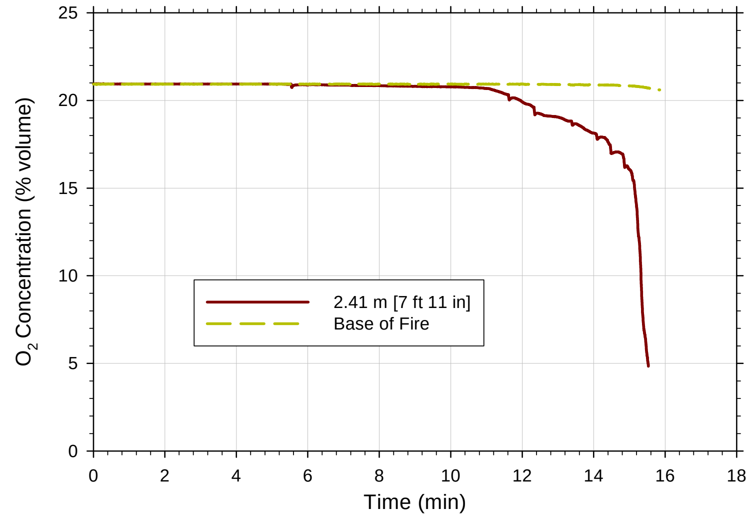
5.5.3 S3 Results – Sofa with Half Open Window

The duration of the test was 120 minutes. The following timeline gives a brief synopsis of the events that occurred during this test.

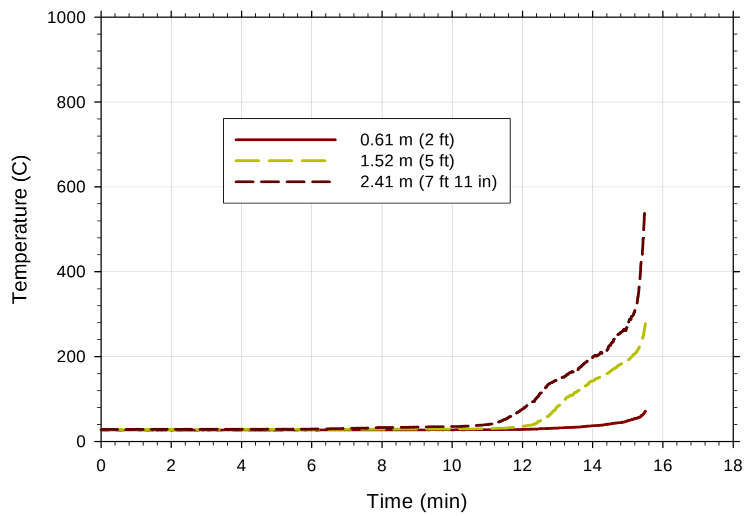




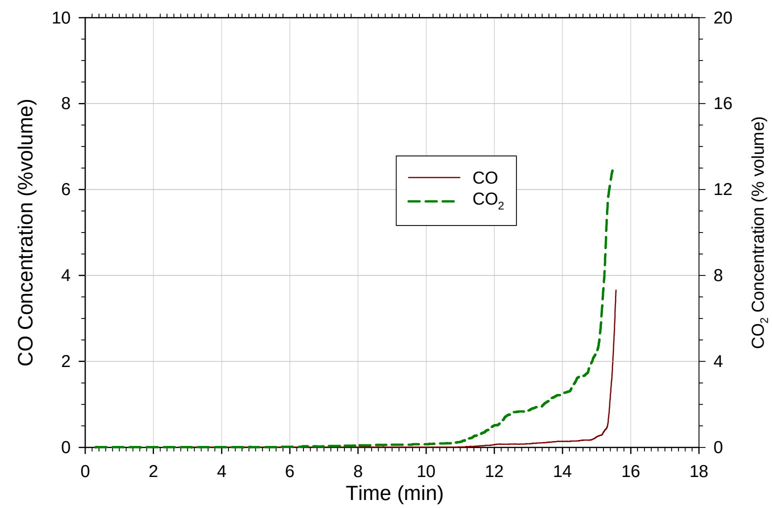
(a) Heat Release Rate



(b) Oxygen Concentrations in Room of Origin



(c) Temperature in Room of Origin



(d) Gas Concentrations at 2.41 m (7 ft 11 in) in Room of Origin

Figure 5-26. Test S2 data – sofa with full open window

The data from this test is presented in Figure 5-28. The peak temperature reached during this test was 630°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 3.4%. The peak CO concentration was 5.5%. The peak CO_2 concentration was 14.3%. The initial mass of the sofa was 49.80 kg. During the test, the total mass loss was 6.75 kg, approximately 14% of the initial mass. The maximum heat release rate calculated during this test was 862 kW. A majority of the material was burned away on the sofa seat, back and interior of the armrests. Also, the center of the front portion had begun to burn away and the wooden frame had begun to char along the back of the sofa (see Figure 5-27).

Figure 5-27. Test S3 damage

5.6 S4 – Accelerated Sofa Test with Half Open Window

This test was designed to simulate an arson scenario involving a sofa. This test used the accelerated flaming ignition scenario and the half open window ventilation scheme. The sofa was placed on the load cell setup in the LR. The armchair was present within the enclosure for this test; however, the coffee table was removed to allow for a clear path for the trailer. A total of 1.0 liter of gasoline was used, with 0.75 L poured on the center of the sofa seat and the remaining 0.25 L used as a trailer to the door. Once the gasoline was poured, the trailer was ignited by a propane torch from the doorway. Once the sofa ignited, the door was closed.

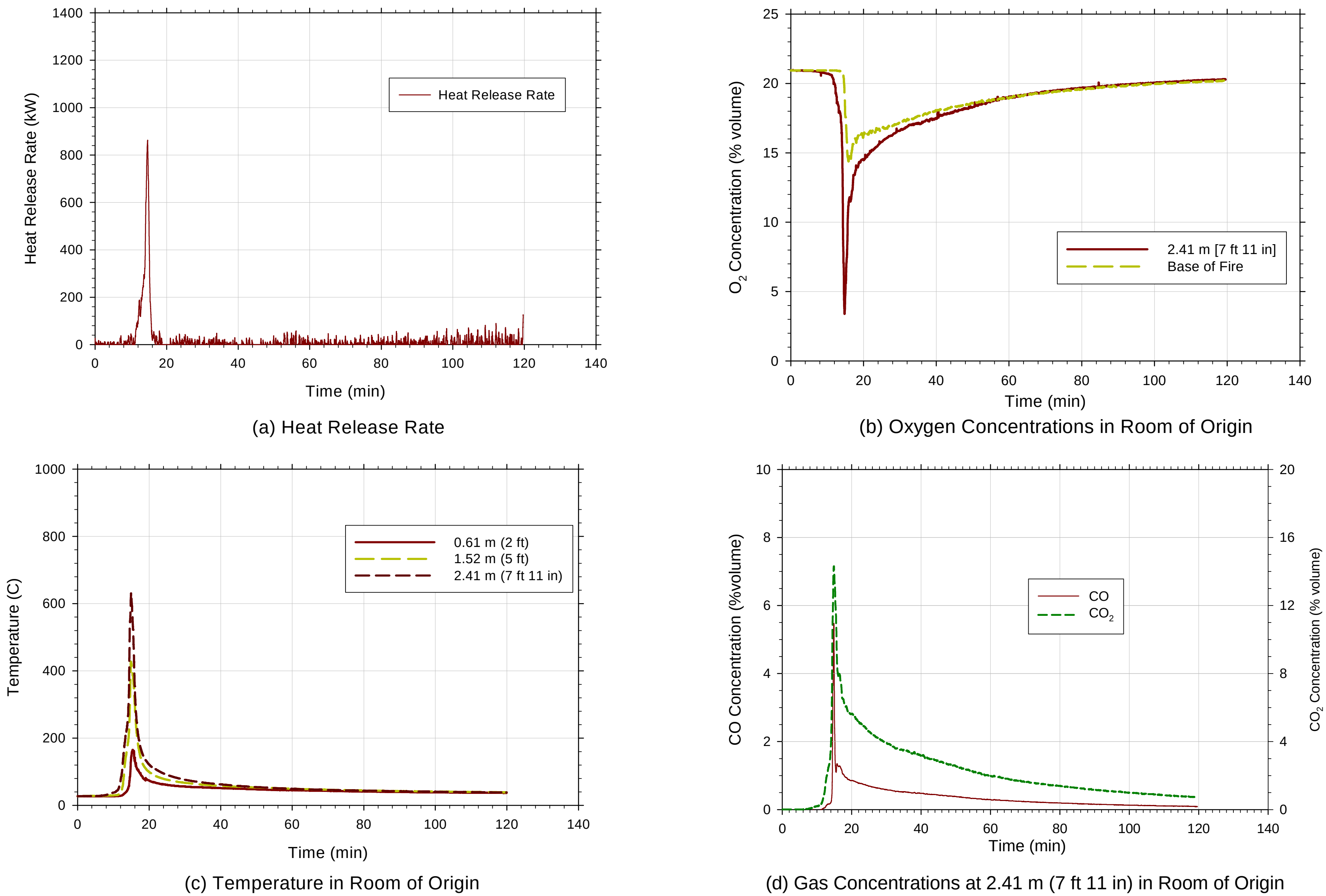
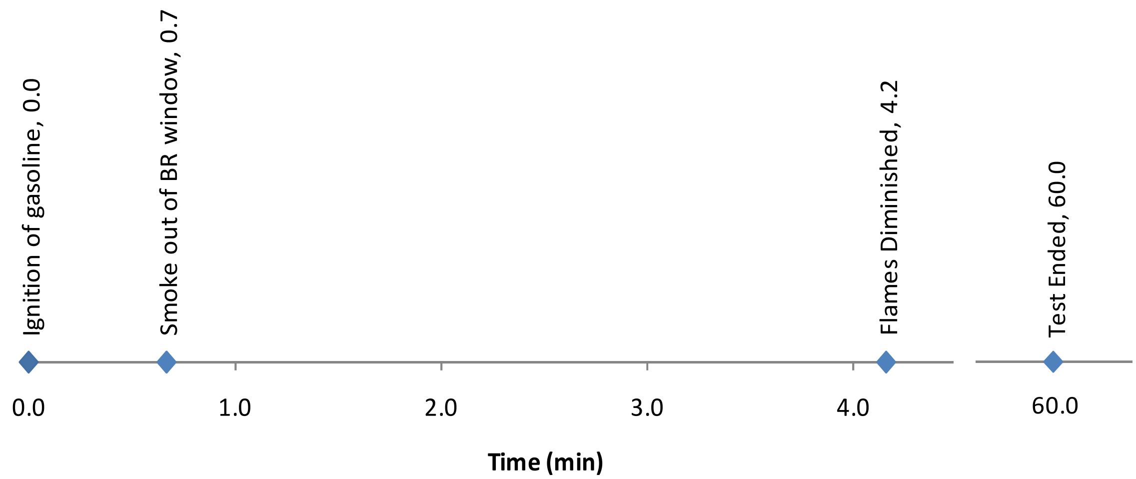


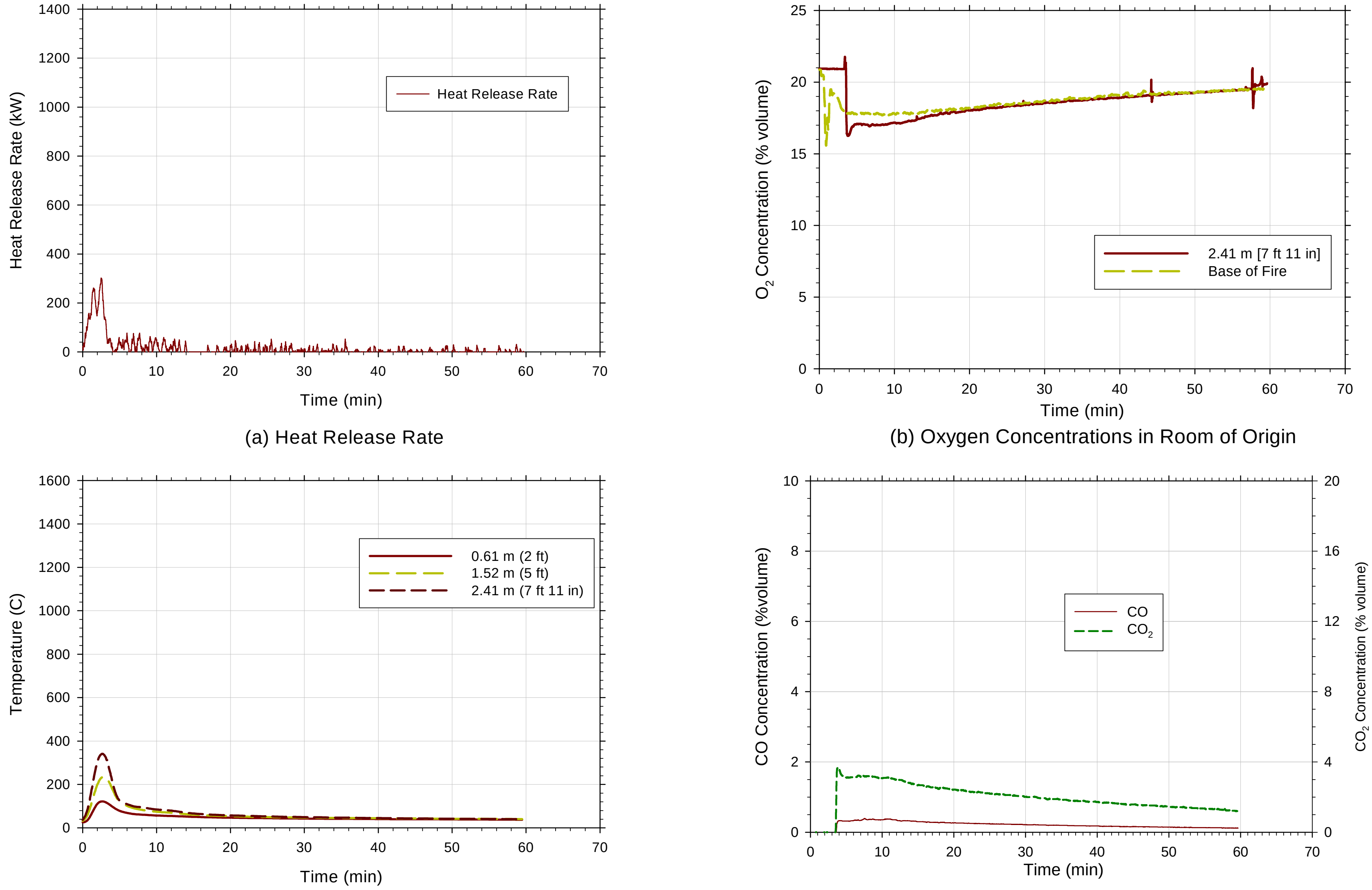
Figure 5-28. Test S3 data – sofa with half open window

The test was allowed to run until the conditions began to return to ambient, a duration of 60 minutes. The following timeline gives a brief synopsis of the events that occurred during this test.



The data from this test is displayed in Figure 5-30. The peak temperature reached during this test was 345°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 16.3%. The peak CO concentration was 0.3%. The peak CO_2 concentration was 3.7%. The initial mass of the sofa was 49.45 kg. During the test, the total mass loss was 3.99 kg, approximately 8% of the initial mass. The maximum heat release rate calculated during this test was 300 kW. The front face and center of the couch where the gasoline had been poured were burned away. The remainder of the seat and back were charred, but not burned away. The most severe charring occurred on the side of the sofa closest to the dining room, and only the inner armrest on that side of the sofa was charred, with the other armrest relatively unchanged aside from soot deposition (see Figure 5-29).

Figure 5-29. Test S4 damage



(a) Heat Release Rate

(b) Oxygen Concentrations in Room of Origin

(c) Temperature in Room of Origin

(d) Gas Concentrations at 2.41 m (7 ft 11 in) in Room of Origin

Figure 5-30. Test S4 data – accelerated sofa with half open window
(2.41 m gas analyzer out of service from test start to 4 minutes)

5.7 CL1, CL2, CL3 –Flaming Low Cabinet Tests

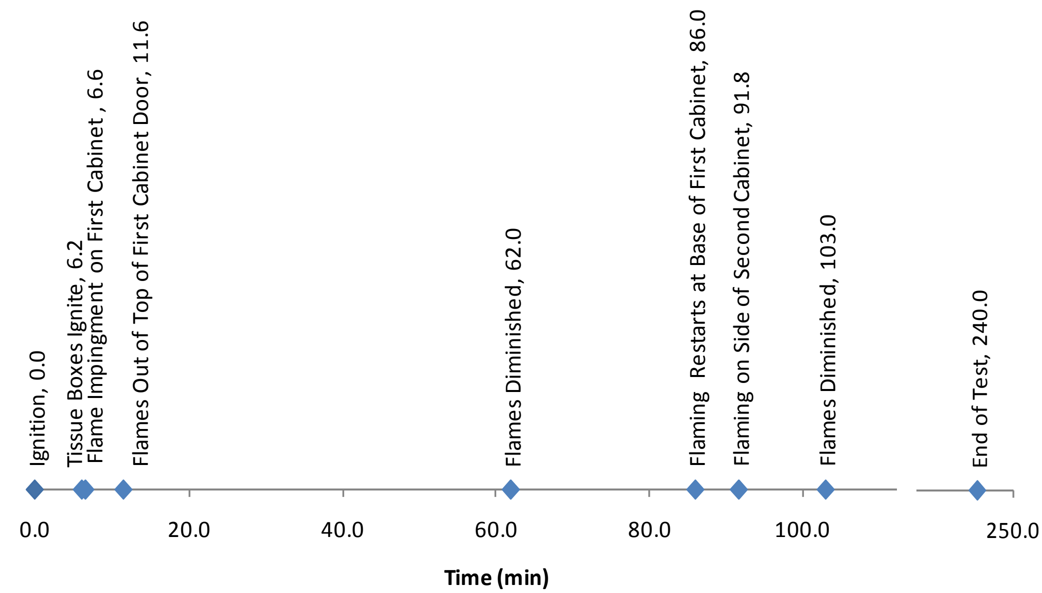
These tests were designed to represent flaming cabinet fires positioned low in the enclosure and initiated by a small flaming source. The cabinets were installed on the false wall in the kitchen space, 0.41 m (1 ft 4 in) above of the enclosure floor (see Figure 5-31). The tissue boxes of the ignition setup were positioned on two 0.012 m (0.5 in) pieces of drywall so that the top of the tissue boxes were 0.051 m (2 in) from the bottom of the leftmost cabinet (see Figure 5-32). The ignition setup was positioned so that the two tissue boxes were directly under the two center tissue boxes on the first shelf of the cabinet, and the front edge of the boxes was even with the front edge of the cabinet. The cap of alcohol was placed on the end of the tissue boxes that was farthest from the false wall. To initiate the test, the alcohol was ignited by a butane lighter. After ignition, all personnel exited the enclosure and the door was closed. These tests were allowed to continue until conditions in the enclosure began to return to ambient. The only difference between these three tests was the ventilation schemes used. Test CL1 had no ventilation, CL2 had half open window ventilation, and CL3 had open door ventilation.

Figure 5-31. Setup for low cabinet flaming tests

Figure 5-32. Ignition scenario for low cabinet flaming tests

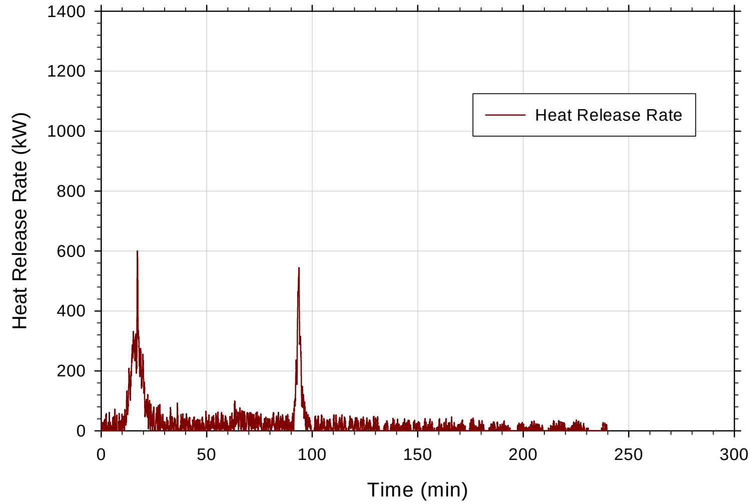
5.7.1 CL1 Results – Low Cabinets with No Ventilation

The duration of the test was 240 minutes. The following timeline gives a brief synopsis of the events that occurred during this test.

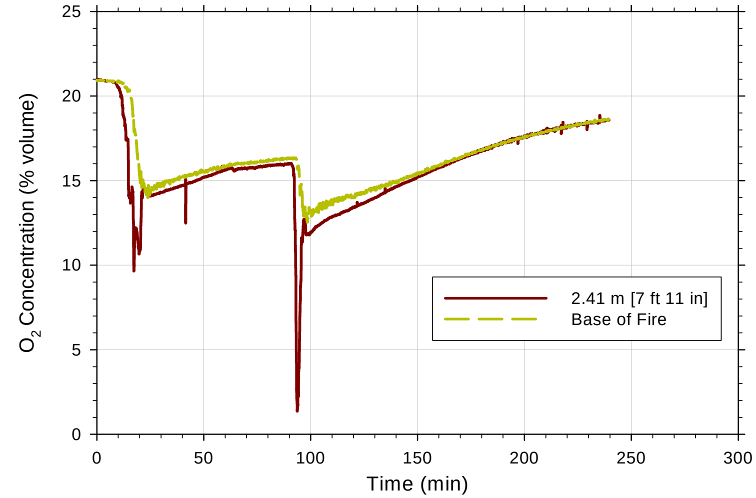


The data for this test is presented in Figure 5-34. The peak temperature reached during this test was 806°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 1.4%. The peak CO concentration was 1.8%. The peak CO_2 concentration was 17.2%. The initial mass of the cabinets was 53.84 kg. During the test, the total mass loss was 30.42 kg, approximately 57% of the initial mass. The maximum heat release rate calculated during this test was 599 kW. The entire first cabinet was consumed, as well as all of the second cabinet except the right side and some of the front frame. There was some charring to the front face of the third cabinet and little damage fourth cabinet

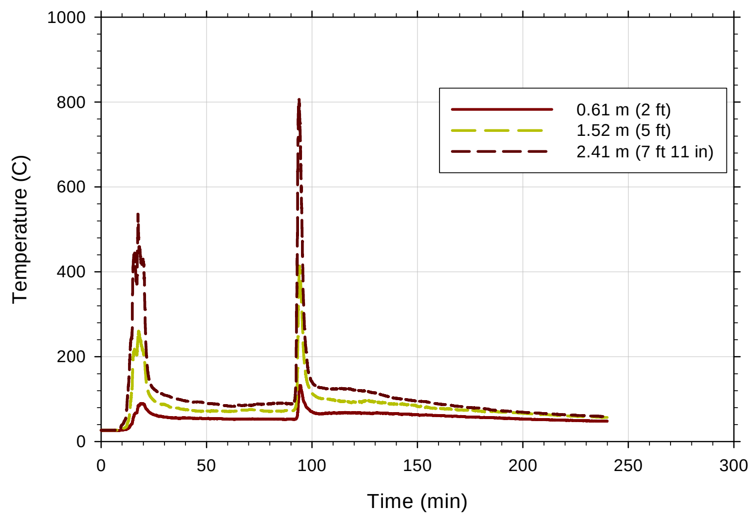
Figure 5-33. Test CL1 damage – low cabinets with no ventilation.



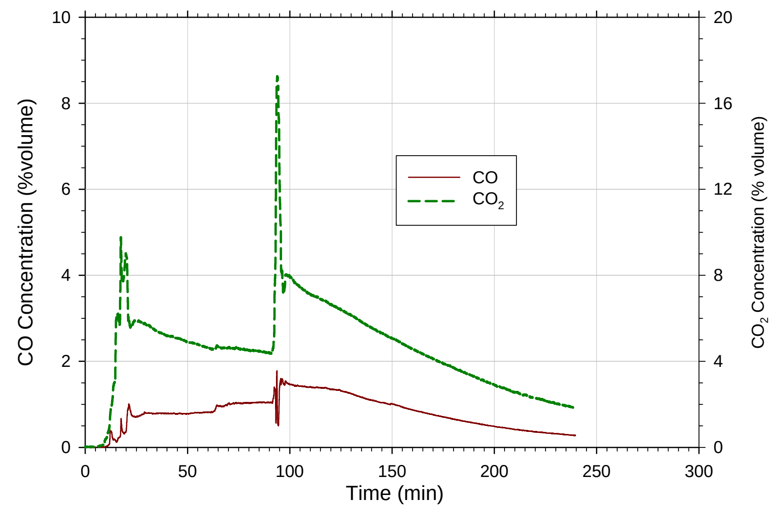
(a) Heat Release Rate



(b) Oxygen Concentrations in Room of Origin



(c) Temperature in Room of Origin

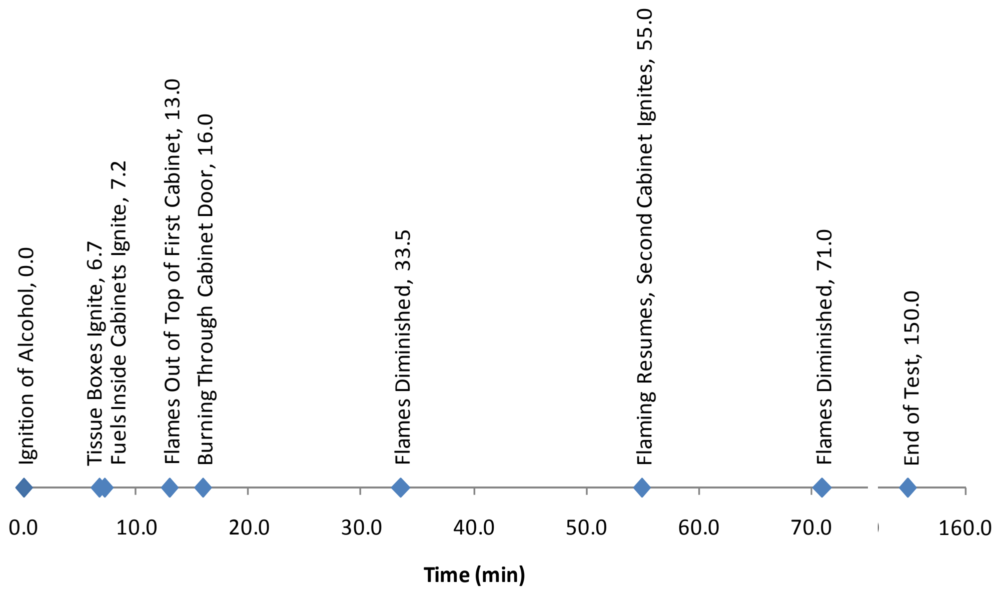


(d) Gas Concentrations at 2.41 m (7 ft 11 in) in Room of Origin

Figure 5-34. Test CL1 data – low cabinets with no ventilation

5.7.2 CL2 Results – Low Cabinets with Half Open Window

The duration of the test was 150 minutes. The following timeline gives a brief synopsis of the events that occurred during this test.



The data for this test is presented in Figure 5-36. The peak temperature reached during this test was 785°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 2.5%. The peak CO concentration was 2.2%. The peak CO_2 concentration was 17.1%. The initial mass of the cabinets was 53.66 kg. During the test, the total mass loss was 30.95 kg, approximately 58% of the initial mass. The maximum heat release rate observed during this test was 595 kW. The majority of the first and second cabinets were completely consumed. Additionally, there was charring present on the top and left side of the front face of cabinet three. There was little damage to the fourth cabinet (see Figure 5-35).

Figure 5-35. Test CL2 damage – low cabinets with half open window

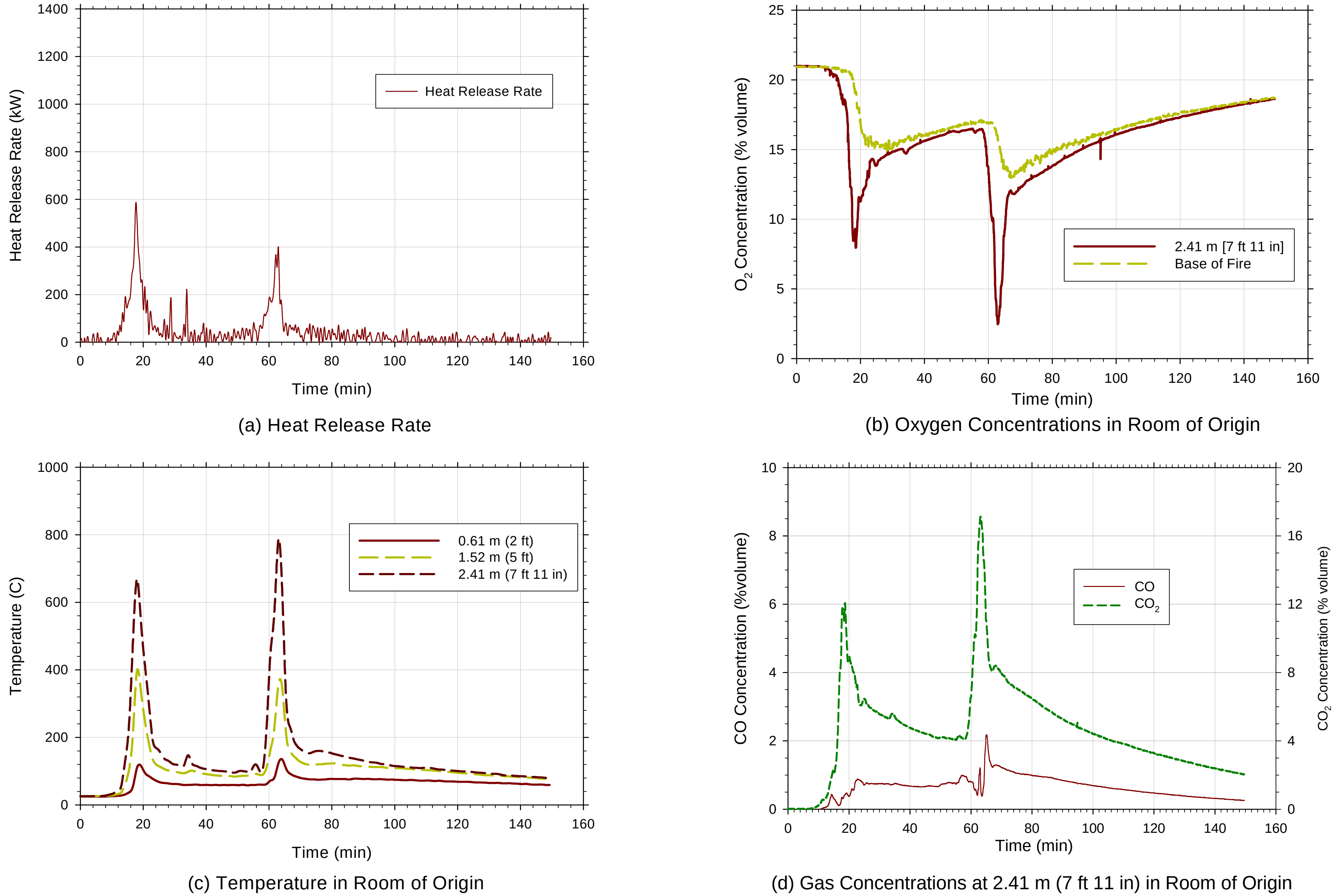
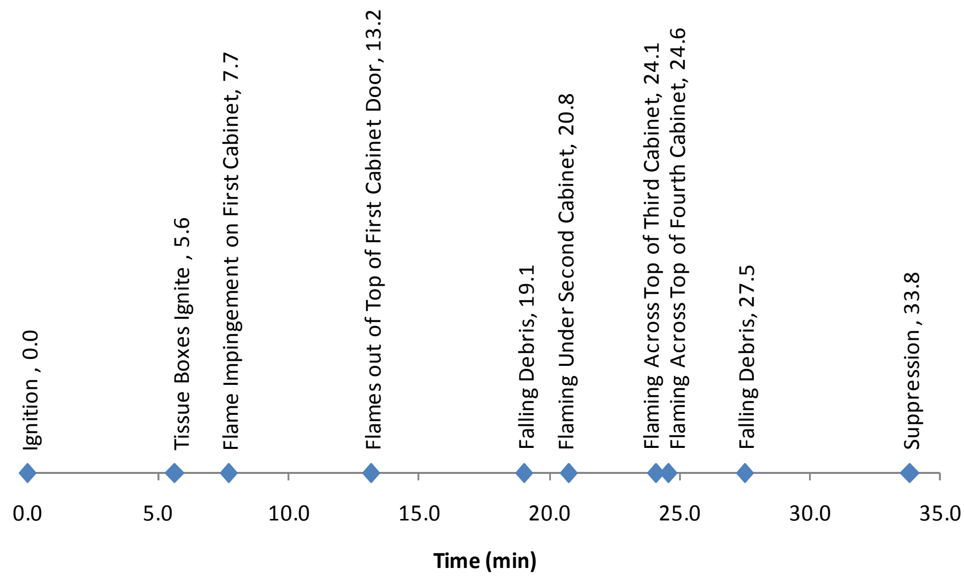


Figure 5-36. Test CL2 data – low cabinets with half open window

5.7.3 CL3 Results – Low Cabinets with Open Door

The duration of the test was 34 minutes. The fire was manually suppressed to prevent extensive damage to the enclosure. The following timeline gives a brief synopsis of the events that occurred during this test.



The data for this test is presented in Figure 5-38. The peak temperature reached during this test was 727°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 5.8%. The peak CO concentration was 0.5%. The peak CO_2 concentration was 13.0%. The initial mass of the cabinets was 53.41 kg. During the test, the total mass loss was 49.87 kg, approximately 93% of the initial mass. The maximum heat release rate calculated during this test was 984 kW. Due to falling debris, the heat release rate data had a few false readings, most notably at 19.05 and 27.50 minutes. The majority of all of the cabinets were consumed during this test (see Figure 5-37).

Figure 5-37. Test CL3 damage – Low Cabinets with Open Door

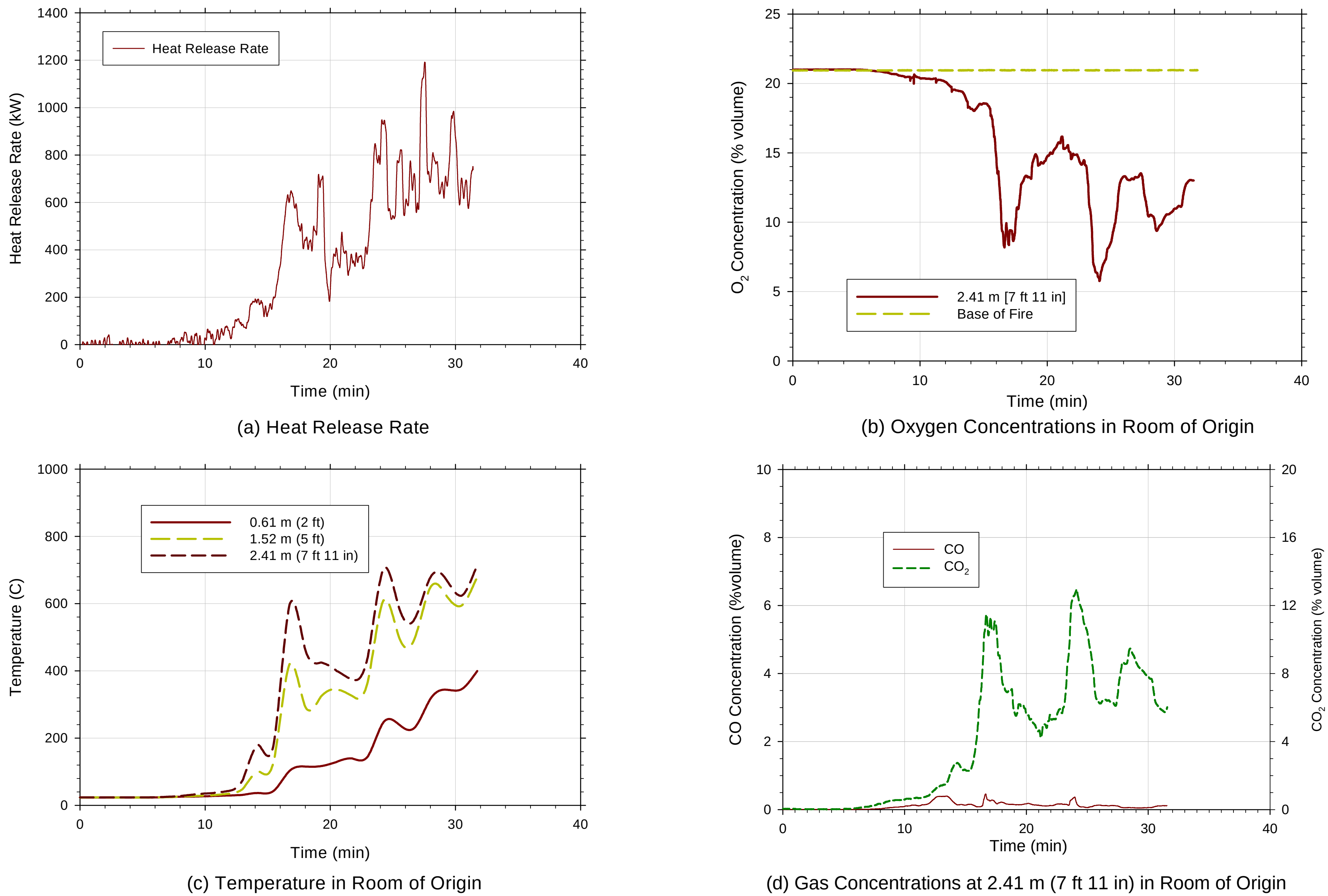


Figure 5-38. Test CL3 data – low cabinets with open door

5.8 CH1, CH2, CH3, CH4 – Flaming High Cabinet Tests

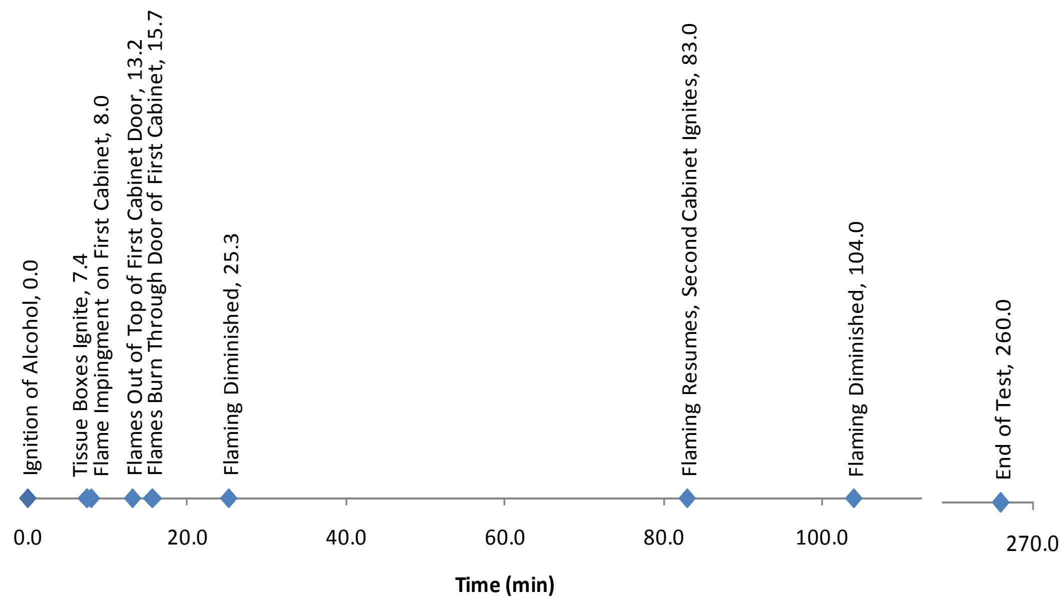
These tests were designed to represent flaming fires in cabinets positioned high in the enclosure and initiated by a small flaming source. The cabinets were installed on the false wall in the kitchen space, 0.41 m (5 ft 2 in) above of the enclosure floor (see Figure 5-39). The ignition source was placed on a shelf constructed of one sheet of 0.012 m (0.5 in) GWB and metal brackets. The tissue boxes were positioned so that the top of the boxes were 0.051 m (2 in) from the bottom of the leftmost cabinet, and the boxes were lined up vertically with the center two tissue boxes on the bottom shelf of the cabinet (see Figure 5-40). The cap of alcohol was placed on the end of the tissue boxes that was farthest from the false wall. To initiate the test, the alcohol was ignited by a butane lighter. After ignition, all personnel exited the enclosure and the door was closed. These tests were allowed to continue until conditions in the enclosure began to return to ambient. The only difference between these four tests was the ventilation schemes used. Test CH1 had no ventilation, CH2 had half open window ventilation, CH3 had the bedroom window removed, and CH4 had open door ventilation.

Figure 5-39. Setup for high cabinet flaming tests

Figure 5-40. Ignition scenario for high cabinet flaming tests

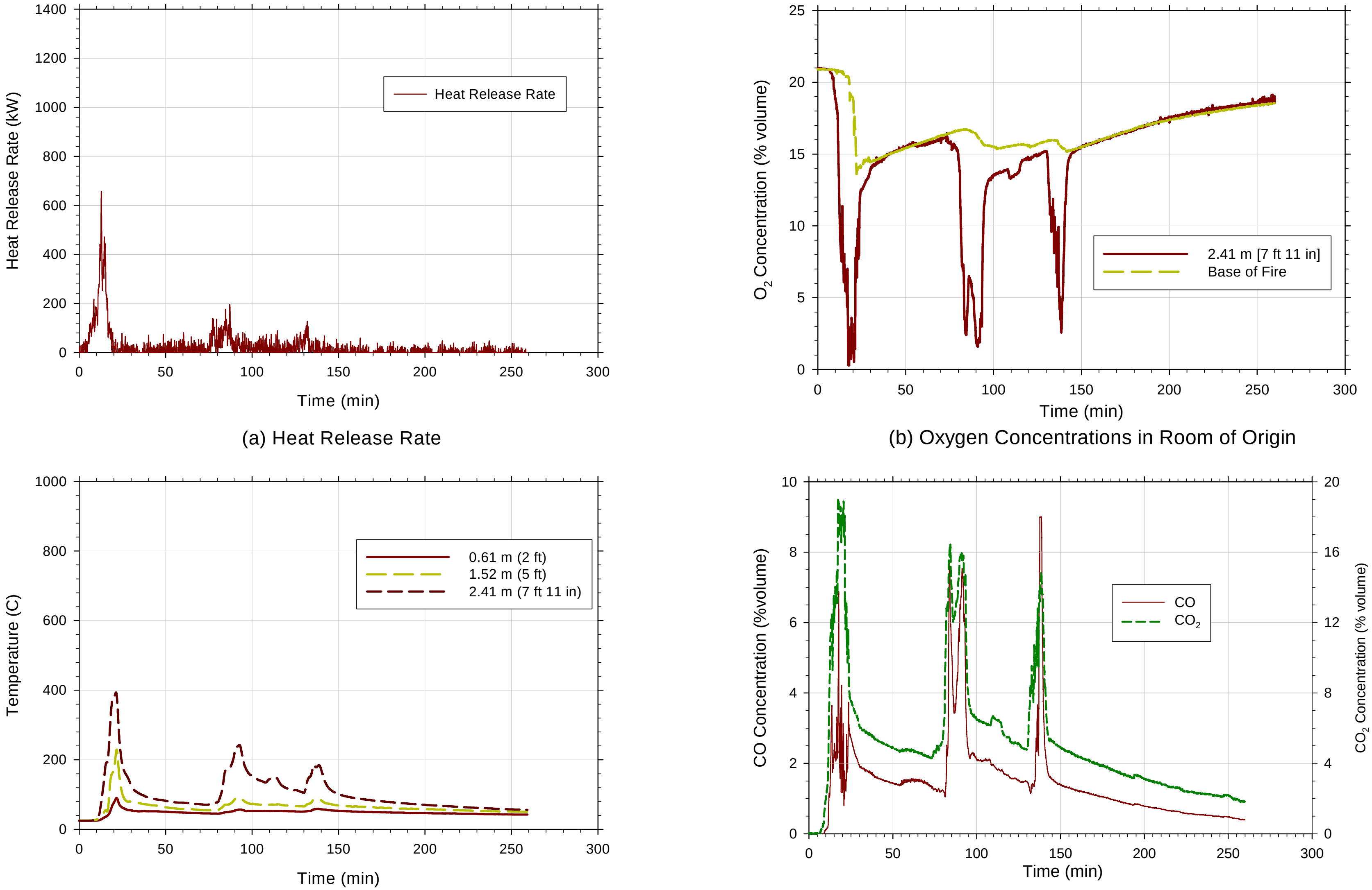
5.8.1 CH1 Results – High Cabinets with No Ventilation

The duration of the test was 260 minutes. The following timeline gives a brief synopsis of the events that occurred during this test.



The data for this test is presented in Figure 5-42. The peak temperature reached during this test was 425°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 0.3%. The peak CO concentration was 9.0%. The peak CO_2 concentration was 19.0%. The initial mass of the cabinets was 55.73 kg. During the test, the total mass loss was 28.77 kg, approximately 52% of the initial mass. The maximum heat release rate calculated during this test was 662 kW. The first was completely consumed during this test. The majority of the frame of the second cabinet was also consumed. In addition, the top half of the third cabinet was consumed and there was substantial charring both inside and out. There was also some charring on the top of the fourth cabinet (see Figure 5-41).

Figure 5-41. Test CH1 damage – high cabinets with no ventilation



(a) Heat Release Rate

(b) Oxygen Concentrations in Room of Origin

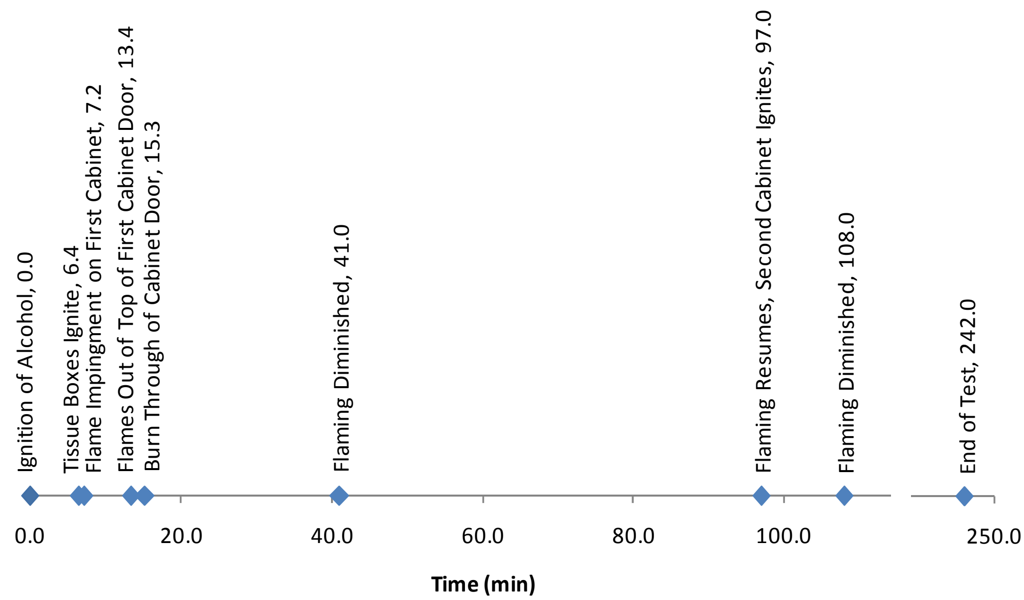
(c) Temperature in Room of Origin

(d) Gas Concentrations at 2.41 m (7 ft 11 in) in Room of Origin

Figure 5-42. Test CH1 data – high cabinets with no ventilation

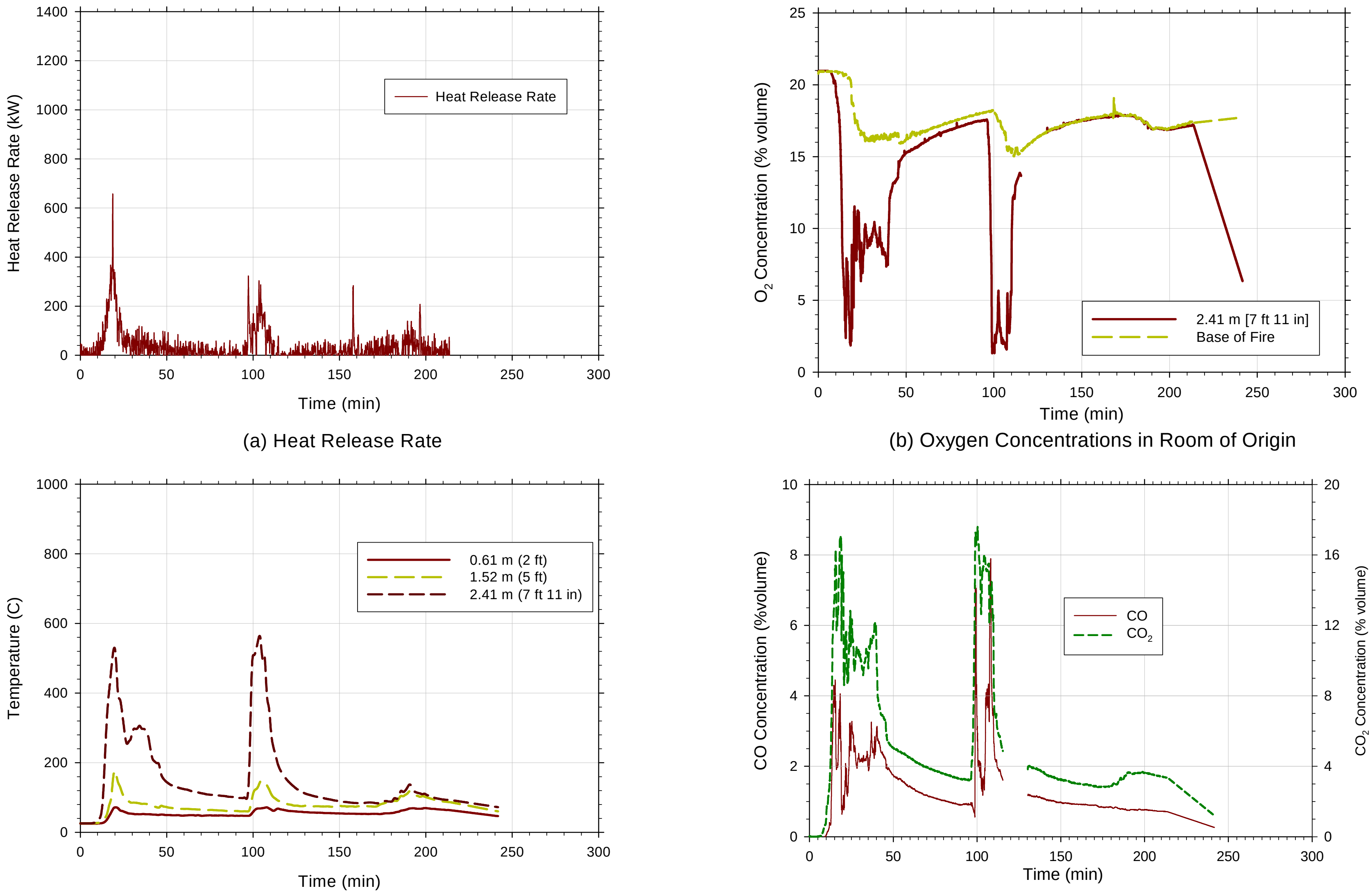
5.8.2 CH2 Results – High Cabinets with Half Open Window Ventilation

The duration of the test was 242 minutes. The following timeline gives a brief synopsis of the events that occurred during this test.



The data for this test is presented in Figure 5-44. The peak temperature reached during this test was 563°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 1.3%. The peak CO concentration was 7.9%. The peak CO_2 concentration was 17.6%. The initial mass of the cabinets was 55.45 kg. During the test, the total mass loss was 40.94 kg, approximately 74% of the initial mass. The maximum heat release rate calculated during this test was 657 kW. The first three cabinets were consumed during the test. The fourth cabinet fell off of the wall sometime during the test. The top frame of the fourth cabinet was consumed, and there was severe charring throughout the rest of the cabinet (see Figure 5-43).

Figure 5-43. Test CH2 damage – high cabinets with half open window



(a) Heat Release Rate

(b) Oxygen Concentrations in Room of Origin

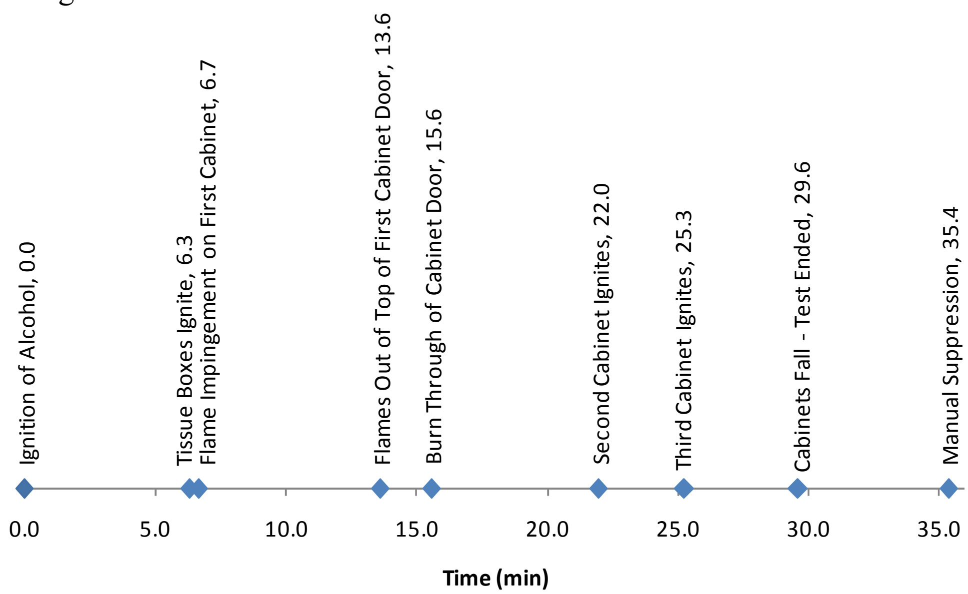
(c) Temperature in Room of Origin

(d) Gas Concentrations at 2.41 m (7 ft 11 in) in Room of Origin

Figure 5-44. Test CH2 data - high cabinets with half open window ventilation (2.41 m analyzer out of service from 115-130 minutes)

5.8.3 CH3 Results – High Cabinets with No Bedroom Window

The duration of the test was 36 minutes. The test was manually suppressed after the cabinets fell from the wall. The following timeline gives a brief synopsis of the events that occurred during this test.

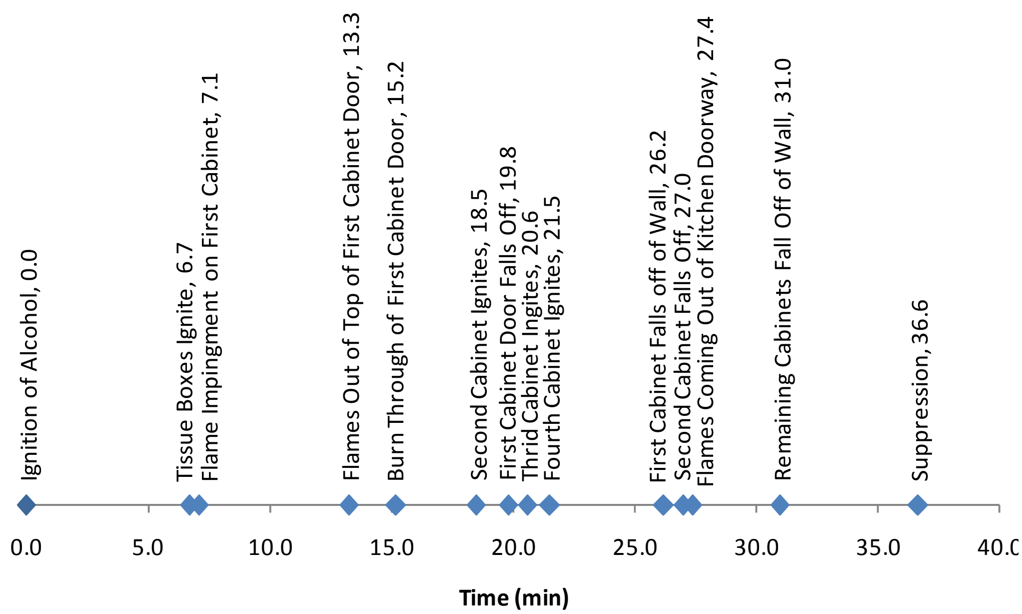


The data for this test is presented in Figure 5-46. The peak temperature reached during this test was 718° C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 5.1%. The peak CO concentration reached was 1.6%. The peak CO_2 concentration was 13.1%. The initial mass of the cabinets was 54.07 kg. During the test, the total mass loss was 29.75 kg, approximately 55% of the initial mass. The maximum heat release rate calculated during this test was 469 kW. The first cabinet and the majority of the second cabinet were consumed during the test. The frame of the third and fourth cabinets remained mostly intact, but had substantial charring throughout (see Figure 5-45). After the cabinets fell at about 30 minutes, the fire started to grow on the floor as the cabinets had fallen from a vitiated upper layer to the lower layer with higher oxygen concentrations. All analyses in this study only consider events up until the time when the cabinets fell so as to consider the effects of the cabinets being high in the space. The fact that the third and fourth cabinets fell early in their involvement was an artifact of the test installation. Due to prior test damage to the wood studs of the false wall that the cabinets were installed to, the screws prematurely pulled out of the studs during the CH3 fire.

Figure 5-45. Test CH3 damage – high cabinets with no bedroom window

5.8.4 CH4 Results – High Cabinets Open Door

The duration of the test was 37 minutes. The test was manually suppressed after the cabinets fell from the wall. The following timeline gives a brief synopsis of the events that occurred during this test.



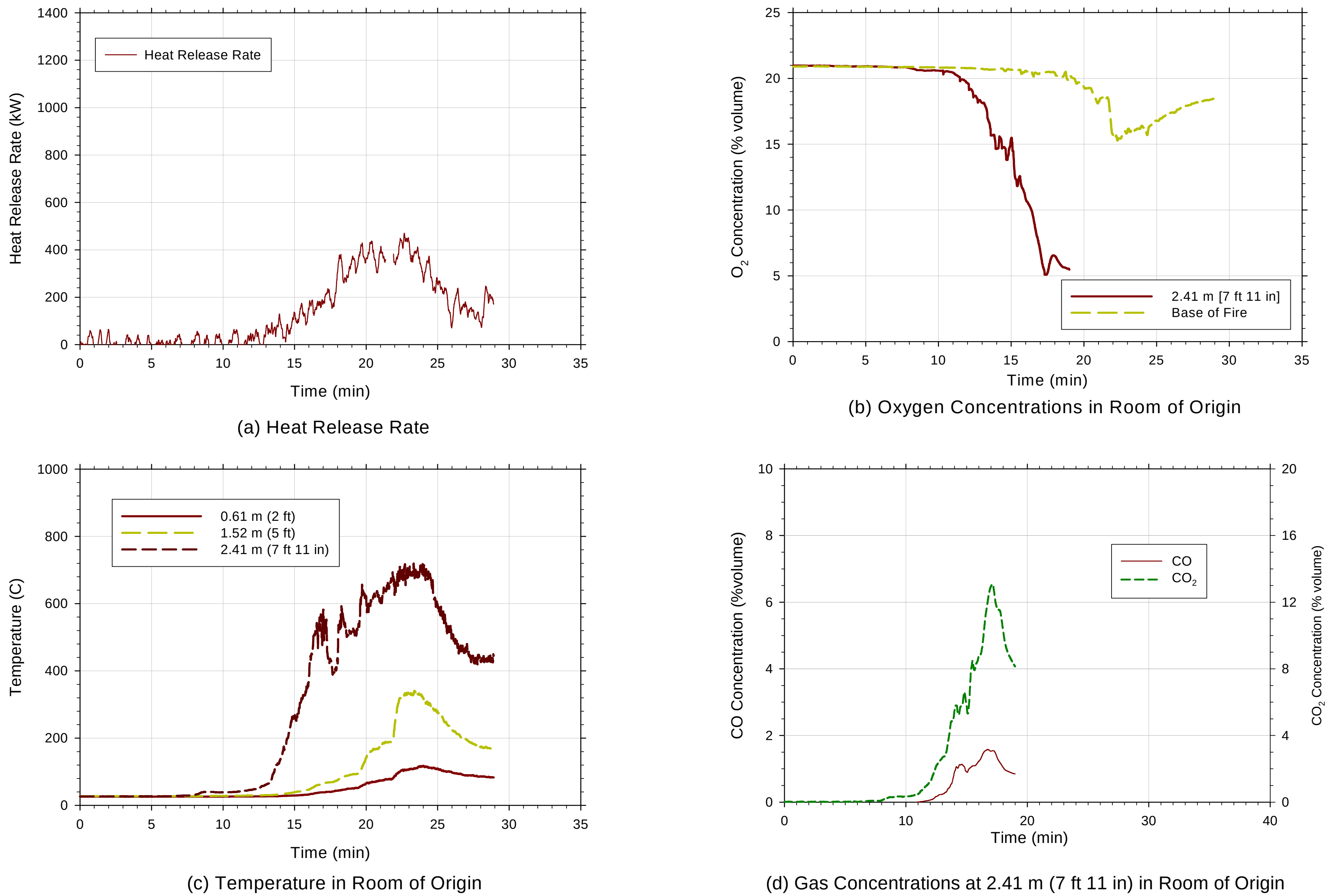
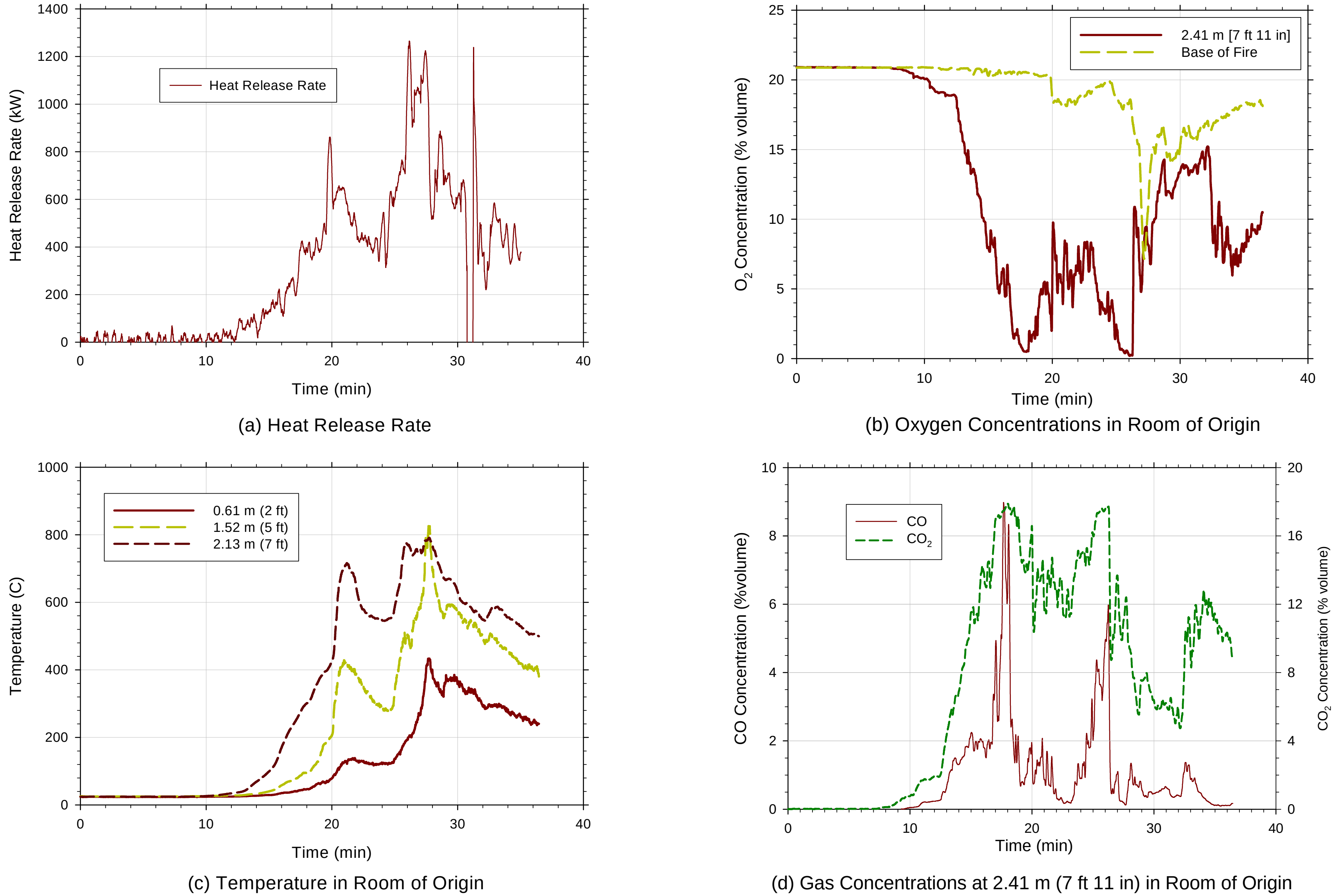


Figure 5-46. Test CH3 data - high cabinets with no bedroom window (2.41 m analyzer out of service after 19 minutes)

The data for this test is presented in Figure 5-48. The peak temperature reached during this test was 829°C. Oxygen concentration at 2.41 m (7 ft 11 in) dropped to a minimum value of 0.2%. The peak CO concentration was 8.9%. The peak CO_2 concentration was 17.9%. The initial mass of the cabinets was 57.93 kg. During the test, the total mass loss was 48.45 kg, approximately 84% of the initial mass. This mass loss only represents the part of the test before the cabinets fell off of the wall, since the test was allowed to continue after the cabinets fell. The parts of the cabinet that fell off of the wall continued to burn on the platform. The maximum heat release rate calculated during this test was 1.1 MW. Due to falling debris, the heat release rate data has several false readings, most notably at 19.8, 26.17, 27.02, and 31 minutes. The majority of the cabinets were consumed; the rest, with most of the GWB from the false wall, were left on the base of the load cell stand (see Figure 5-47).

Figure 5-47. Test CH4 damage – high cabinets open door



(a) Heat Release Rate

(b) Oxygen Concentrations in Room of Origin

(c) Temperature in Room of Origin

(d) Gas Concentrations at 2.41 m (7 ft 11 in) in Room of Origin

Figure 5-48. Test CH4 data - High Cabinets Open Door (2.41 m TC malfunctioned during test, 2.13 m TC shown)

6 VENTILATION EFFECTS ON ENCLOSURE FIRE DYNAMICS

6.1 Fire Growth

Changing the ventilation of a fire scenario had an impact on the growth and progression of the fire. The heat release rate, temperature rise, and gas concentrations depended upon the amount of ventilation a fire had available. For the flaming fires, the amount of ventilation directly influenced the heat release rate. The greater the ventilation in a test, the higher the peak heat release rate. Table 6-1 shows the ventilation and the burning duration for each test. Burning duration was determined as the amount of time elapsed from when a fire grew above 50 kW to the point it fell below 50 kW. Sofa Test S4 is not considered because it used a different ignition scenario (gasoline) than the other two sofa tests. For tests CL3 and CH4, there are cases of anomalies in the heat release data (e.g., spikes) due to large amounts of debris falling from the cabinets. The times of these anomalies have been tabulated in Table 6-2. For the purposes of comparing heat release rates, these anomalies have been discounted. In addition, test CH3 is excluded from subsequent analysis due to the cabinets falling off the wall and the test being ended prematurely.

Table 6-1. HRR and Burning Duration Based on Ventilation

Test	Ventilation	Vent Area (m^2)	Peak HRR (kW)	Duration of Burning (min)	Mass Consumed During Burning (kg)
S1	No Ventilation	0	353	6.2	3.4
S3	Half Open Window	0.12	862	4.6	5.7
S2*	Full Open Window	0.24	1032	4.3	4.8
CL1	No Ventilation	0	599	11.5	10.4
CL2	Half Open Window	0.12	595	11.7	11.1
CL3*	Open Door	1.85	984	>21.8	48.7
CH1	No Ventilation	0	662	13.3	13.7
CH2	Half Open Window	0.12	657	13.4	12.5
CH3**	BR Window Removed	0.67	469	>14.9	25.1
CH4*	Open Door	1.85	1071	>24.1	47.9

* - Manual suppression used (at 15.9 min in S2, at 33.8 min. in CL3, and at 36.6 min. in CH4). Tests CL3 and CH4 were mostly finished burning at time of suppression.

** - Cabinets fell off of the false wall in test CH3 at 29.6 minutes. Analysis was discontinued at this time.

Table 6-2. Anomalies in HRR Data

Test	Time of Anomaly (min)
CL3	19.05, 27.50
CH4	19.80, 26.28,27.02, 31.00

It is clear that for the sofa fires, the added ventilation greatly increased the size of the fire, raising the maximum heat release rate 509 kW from the no ventilation scenario to the half open window scenario, and another 170 kW from half open to full open window. Figure 6-1 shows a progression of the heat release rates for the sofa fires until minimum burning during the vitiated phase. For the low cabinet and high cabinet scenarios, the change from no ventilation to the half open window resulted in about the same peak heat release rate and did not yield the same large increase as seen with the sofas. When exposed to the open door scenario however, there is a large difference for both the high and low cabinets peak heat release rates compared to the half window vent. Figure 6-2 and Figure 6-3 show the heat release rates for low and high cabinets respectively. Only the initial heat release rate rise is shown to compare the peak heat release rate and time to vitiated burning. With a full open door, the peak heat release rates were approximately twice as high as for the fires with the half open window and no ventilation.

The amount of ventilation also had an effect on the burning duration, mostly during the sofa tests. For both high and low cabinet tests, the no ventilation scenarios burned for about the same duration than the half open windows; the difference was within 0.2 minutes (12 seconds) for both cabinet arrangements. The open door cabinet tests never decreased below the 50 kW threshold before suppression or cabinets falling.

The difference in burning duration for the sofa tests was slightly more pronounced, with the no ventilation scenario burning 1.23 minutes shorter than the half open window. The full open window test (S2) cannot be accurately compared since the fire was still burning when it was manually suppressed, thus stopping the burning duration short of where it could have potentially been. This data is in agreement with the peak heat release data in that the more oxygen the fire has, the longer it can burn and the larger the fire can become.

It is evident that ventilation can greatly influence the growth and extent of burning. In addition, the amount of ventilation needed to maintain sustained burning is dependent on the fuel type and configuration. For sofa tests, the critical ventilation size is greater than the half open window. At the time of manual suppression for the full open window scenario (S2), the oxygen concentration at the base of the fire was still above 20%. However, whether this fire would have become vitiated and suppressed or led to flashover cannot be stated for sure. Based on the rapid increase in the heat release rate and the oxygen level high in the living room plummeting similar to that in test S3, it is anticipated that the full open window fire would have become vitiated as well.

For cabinet fires, the critical ventilation size lies between the half open window and open door scenario, since the half open window test became vitiated and the open door did not. The critical vent size for cabinets can be inferred to be larger than the sofa, due to the fact that the change from no ventilation to half open window ventilation had a more pronounced effect on heat release rate in the sofa fires than it did on cabinet fires.

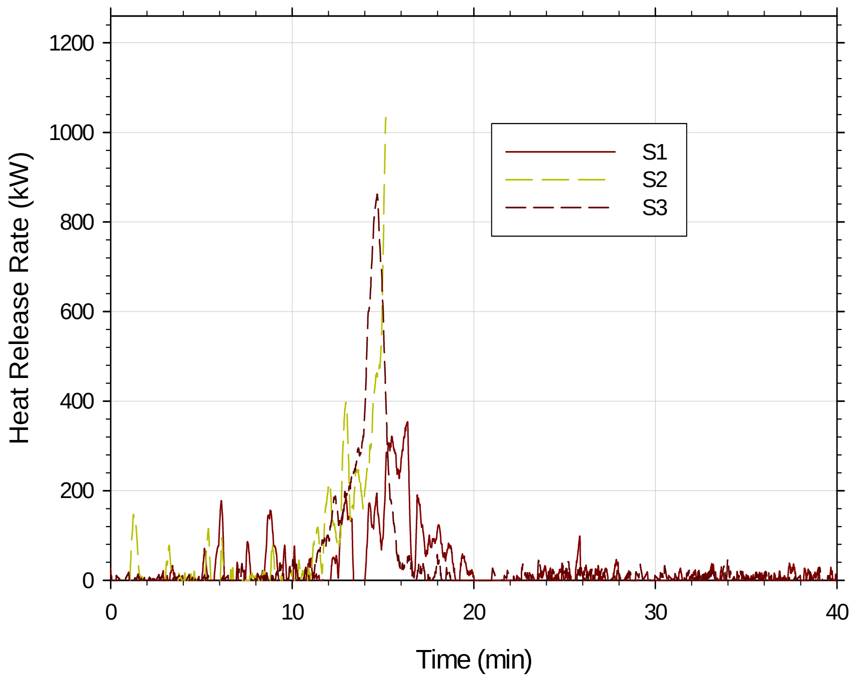


Figure 6-1. Initial HRR development for sofa fires

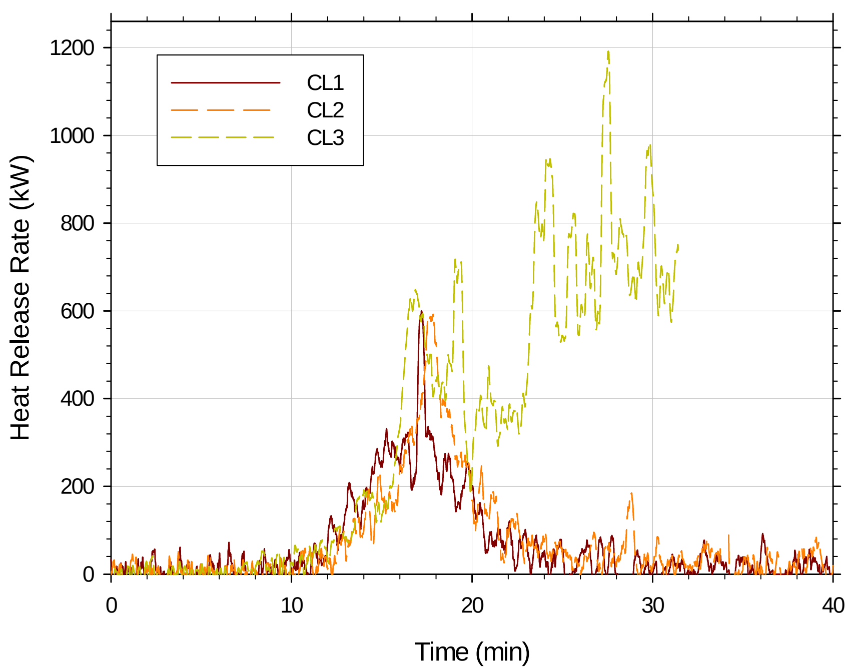


Figure 6-2. Initial HRR development for low cabinet fires

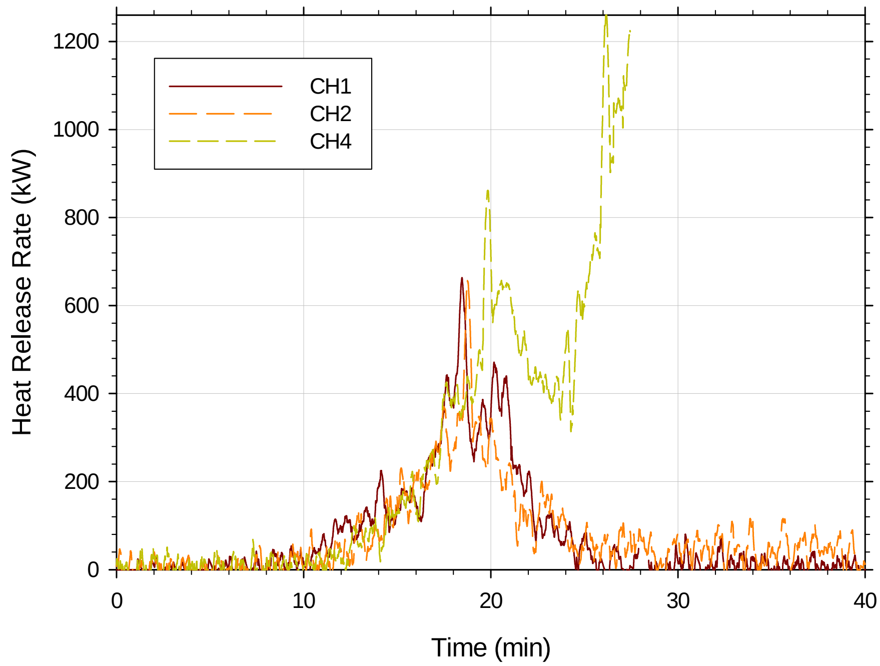


Figure 6-3. Initial HRR development for high cabinet fires

6.2 Lower Oxygen Index

The lower oxygen index (LOI) is the oxygen concentration at the flammability limit (Beyler, 2008). For the compartment fire tests, the oxygen at the base of the fire was measured to determine the LOI at which the fire became suppressed. The fires may not have fully extinguished in all cases. As will be seen via the data, the fires extinguished or substantially decreased in size when the oxygen concentration at the base of the fire decreased below a critical value. For the cabinet fires that were suppressed (possibly extinguished), the fire reignited or began to grow when the oxygen concentration rose back above the same critical value. The LOI was determined using two criteria. One criterion evaluated the LOI as the oxygen concentration at the base of the fire at the time when the ceiling level, 2.41 m (7 ft 11 in), oxygen concentration sharply changed. The points of interest were just prior to large increases and large decreases (after having been suppressed) in the ceiling level oxygen, which signified that the fire either had reached a limiting concentration and could not be sustained or there was now enough oxygen to allow the fire to grow, respectively. Figure 6-4 shows an example of this approach using the oxygen concentrations in test CL1. The vertical red lines signify where the sharp changes were in the 2.41 m (7 ft 11 in) oxygen concentration, which is where the base of fire oxygen concentration was recorded and used to determine the LOI.

Table 6-3 shows the data obtained from this method.

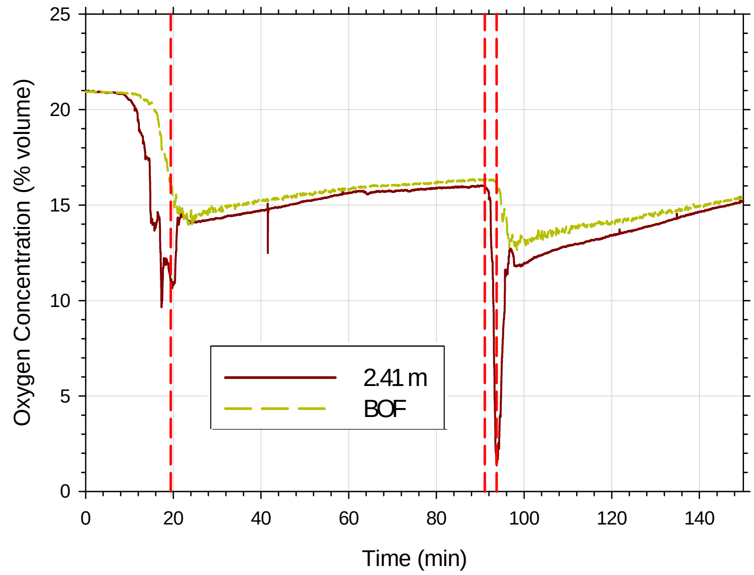


Figure 6-4. Oxygen concentration method of determining LOI at base of fire (BOF) for test CL1

The second approach to identifying the LOI was to examine the base of fire oxygen concentration at the time that the overhead temperature either peaked in the fire room and started to decline or before the temperature rose sharply after the fire had been suppressed. Figure 6-5shows the temperature and base of fire oxygen time histories for test CL1. The vertical lines show where the temperature data sharply changed and the oxygen was evaluated. Using these concentrations, an approximate LOI was determined for each test. Tests CL3, CH3, and CH4 were not included because there was not a significant decline in burning before the tests were ended; these fires were deemed not to have been suppressed due to vitiation.

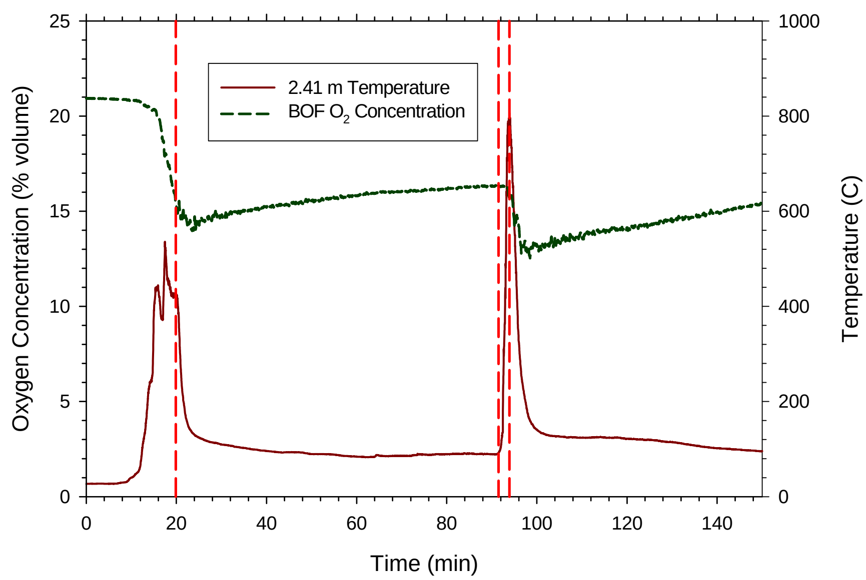


Figure 6-5. Temperature method of determining LOI for test CL1

Table 6-3. 2.41 m Oxygen Concentration Method Data

Test	Time	2.41 m O_2	BOF O_2	2.41 m CO
S1	16.53	15.88	19.43	0.21
S3	14.80	3.39	19.25	5.28
S4	Analyzer Out of Service			
CL1	19.42	10.98	16.04	0.35
	91.02	16.01	16.34	1.05
	93.73	1.37	15.90	1.76
CL2	18.55	7.96	19.10	0.41
	58.03	16.47	16.95	0.95
	62.98	2.46	15.76	1.21
CH1	20.67	0.52	16.39	2.53
	73.07	16.35	16.38	1.32
	91.13	1.59	16.16	7.30
	130.13	15.21	15.89	1.45
	138.58	2.57	15.48	8.99
CH2	38.73	7.36	16.39	2.70
	96.00	17.59	18.10	0.90
	107.28	1.57	15.77	3.29

Highlighted rows are before oxygen concentration decline.
Non-highlighted rows are before oxygen concentration rise.

Table 6-4. Temperature Method Data

Test	Time	2.41 m O_2	BOF O_2	2.41 m CO
S1	15.8	16.48	20.33	0.24
S3	15.0	4.69	17.73	4.34
S4	3.0	N/A	18.16	N/A
CL1	19.9	10.83	15.48	0.35
	91.5	15.86	16.34	1.02
	93.9	1.75	15.72	1.77
CL2	18.5	8.18	19.16	0.40
	54.0	16.44	16.83	0.76
	62.8	2.80	16.00	1.12
CH1	21.2	1.99	16.71	1.54
	80.0	14.58	16.64	1.21
	93.3	3.33	15.84	4.58
	129.7	15.18	15.88	1.48
	135.7	8.82	15.95	2.35
CH2	19.4	5.07	18.74	0.65
	27.5	9.50	16.19	2.26
	34.2	9.03	16.28	2.26
	96.5	17.40	18.15	0.95
	106.9	1.76	16.19	4.30

Highlighted rows are before temperature rises.
Non-highlighted rows are temperature peaks.

The data from both methods match relatively well. For the cabinets, almost all points of interest sampled had a base of fire concentration of approximately 16% by volume. This finding suggests that this concentration is the LOI for the cabinet fire tests. For the sofas, the base of fire oxygen concentrations were approximately 18-20% by volume. Since polyurethane foam was the principle component of the sofa fires, these tests indicate that the LOI for the foam was 18-20%. In comparison with data reported by Cullis and Hirschler for polyurethane foam (16.5%), the values for this study are higher (Cullis & Hirschler, 1981). No published values for solid wood were found for comparison.

It is recognized that the size of the test structure (independent of the ventilation) can impact greatly when and if a specific size fire will become vitiated. Current fire models, such as Fire Dynamics Simulator (Boehmer, Floyd, & Gottuk, 2009), can be used to calculate the oxygen concentrations in any given structure relative to a specific fire scenario. By knowing the LOI for a fuel, the modeling can account the suppression of the fire based on the vitiation of the space. The results of this study were used to validate the Beyler unified model of fire suppression based on the fire point equation to calculate the LOI (Beyler, 1992). Using this method, the critical oxygen concentration value was determined by a modeling equation that takes into account heat capacity and dilution effects by using material properties and experimental data. The procedure and results of this validation can be found in Appendix 0. Overall the results were in general agreement with the LOI values determined in this section. This validation of the of the fire point theory method demonstrates that the LOI data from this study and the unifired model of fire suppressioncan be used in analyzing other real world fires that occur in different size structures and with different fires. This modeling tool will aid investigators in determining when or if a fire became underventilated.

6.3 Smoke Layer Development

To analyze smoke layer development, measurements of optical density were used. Optical density measurements were taken at elevations of 0.61 m (2 ft), 1.52 m (5 ft), and 2.41 m (7 ft 11 in). The optical density per meter was calculated using Bouguer's Law (Klote & Milke, 2002).

$$D = -\frac{1}{L}\log\left(\frac{I}{I_o}\right)$$

where

Dis the optical density per meter
Lis the path length (1.52 m)
$I_o$is the intensity of the light in clear air (i.e., background)
Iis the intensity of the light detected by the photocell at a specific time.

An optical density per meter of 0.43 was used as a threshold criteria to indicate when the upper layer had descended to the elevation of the measurement. This optical density corresponds to a visibility of approximately 2 m (6.6 ft) and represents a potential hindrance to escape (ISO/DTS 13571, 2001).

Table 6-5 displays the time to the target optical density at each elevation in the living room and bedroom.

Table 6-5. Time (min) to an Optical Density per meter of 0.43

Test	Ventilation	Height					
		Living Room			Bedroom		
		0.61 m	1.52 m	2.41 m	0.61 m	1.52 m	2.41 m
S1	No Ventilation	14.35	12.52	12.08	13.83	13.20	12.55
S3	Half Open Window	13.77	12.00	11.63	13.43	12.67	12.12
S2	Full Open Window	14.35	12.15	11.62	13.73	12.78	12.17
CL1	No Ventilation	15.65	13.32	12.48	15.00	13.83	12.85
CL2	Half Open Window	17.07	14.48	13.82	16.30	14.98	14.15
CL3	Open Door	31.73	13.02	11.43	17.82	13.93	12.48
CH1	No Ventilation	17.88	14.60	12.57	17.85	16.78	14.10
CH2	Half Open Window	18.75	15.78	14.03	17.92	17.03	15.35
CH3	BR Window Removed	19.83	16.27	14.72	19.60	17.95	15.05
CH4	Open Door	27.33	16.28	13.50	18.52	16.68	14.45

Figure 6-6 and Figure 6-7 show graphical comparisons of when the tests reached the target optical density at each sample elevation in the living room and bedroom. It can be seen from these figures that for each fuel source, the difference between ventilations is generally only on the order of approximately two minutes. Even across all of the fuel sources, the target optical density is generally reached within five minutes, particularly at the high elevation. Test CL3 and CH4 were low and high cabinet tests with open door ventilation. The open door caused the layer height to remain higher in the living room for a longer period of time; that is why the smoke level did not decrease to 0.43 m^{-1} at the 0.6 m height until much later compared to the other tests. There is also a general trend that the sofa reached the target first, then the lower cabinets, then the upper cabinets. This trend is consistent with the relative fire developments as shown in the heat release rate data.

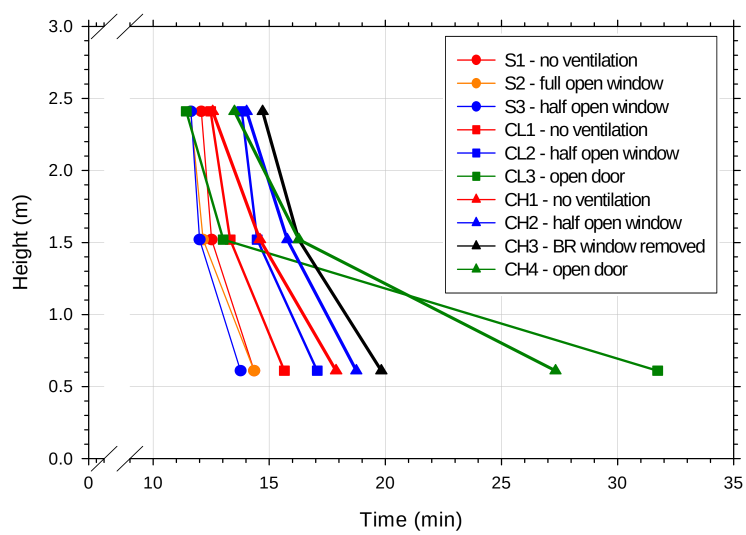


Figure 6-6. Time to 0.43 optical density per meter at sample elevations in the living room for all tests

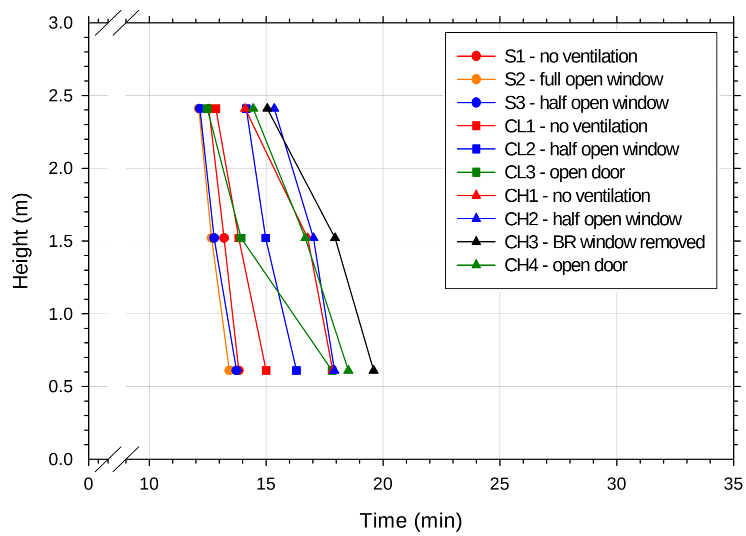
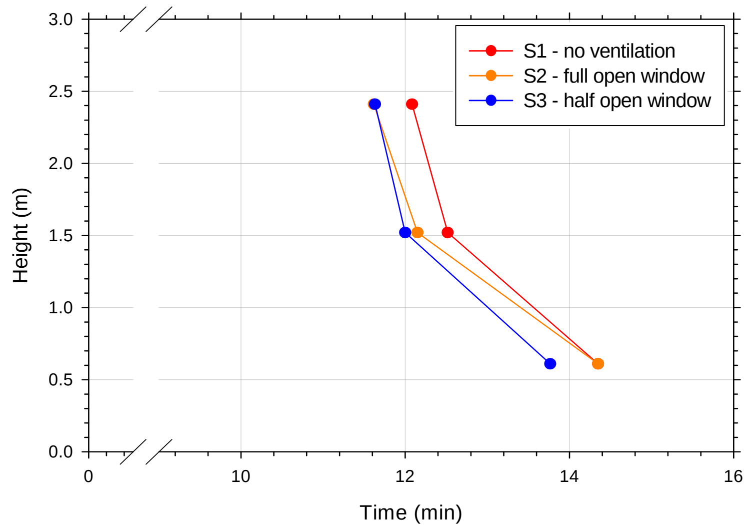
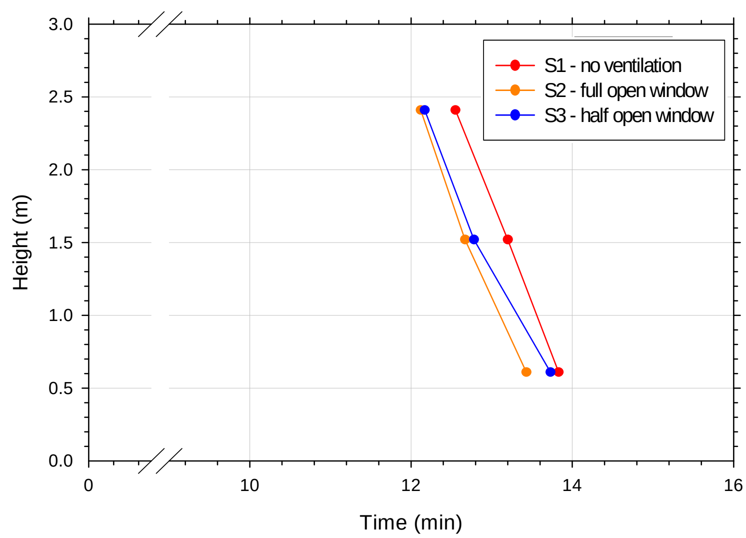


Figure 6-7. Time to 0.43 optical density per meter at sample elevations in the bedroom for all tests

Figure 6-8 shows a graphical representation of the time to target optical density for the sampled heights during the sofa tests. In general, the no ventilation and half open window scenarios took approximately the same amount of time to reach the target optical density, with the full open window slightly after. However, all of the times for both rooms are within approximately 30 seconds of one another. Based on these facts, it would seem that the different ventilation schemes made little impact on the time to reach the target optical density during the sofa fires. In addition, all of the tests have approximately the same general pattern and slope on the graph, indicating that the layer dropped to each elevation at a similar rate within each room. The bedroom appears to have accumulated smoke at a much more linear rate than the living room. In the living room the rate of smoke accumulation was greater from 2.41 m to 1.52 m than from 1.52 m to 0.61 m.



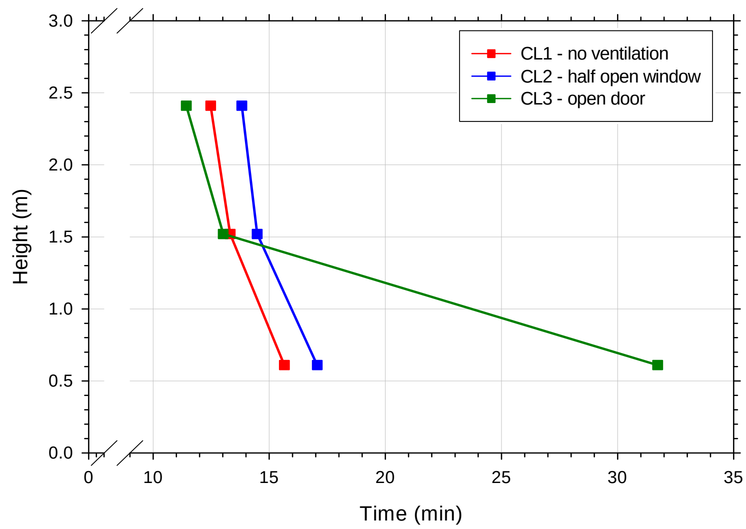
a. Living room



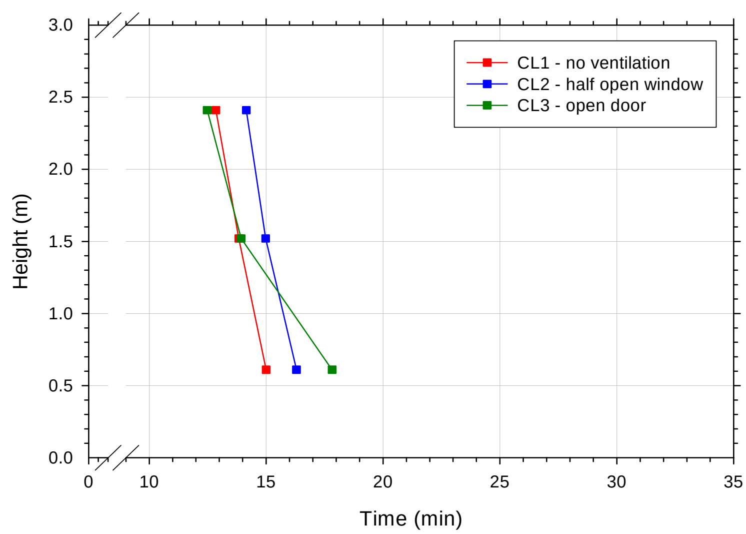
b. Bedroom

Figure 6-8. Time to 0.43 optical density per meter at sample elevations for sofa tests

Figure 6-9 shows a graphical representation of the time to target optical density for the low cabinet fire tests. The different scenarios reached the target optical density within two minutes of each other at both the 2.41 m (7 ft 11 in) and 1.52 m (5 ft) elevations. At the 0.61 m (2 ft) location, the open door test took much longer to reach the target. As observed in the sofa tests, the slopes of the lines can give insight into the layer development. Tests CL1 and CL2 have near identical slopes in both rooms, showing that the layers in these tests developed similarly. In test CL3 with the open door, the fire reached a higher peak heat release rate faster than the other two tests (see Fig. 1-2); however, due to the large ventilation opening in the living room, the layer did not descend as rapidly to the 0.61 m elevation, especially in the living room. Consequently, the smoke did not build up to the 0.43 m^{-1} level until later in the test. This effect was observed to a much lesser degree back in the bedroom, away from the LR door vent. The smoke level at the 0.61 m elevation reached 0.43 m^{-1} in about half the time as in the living room.



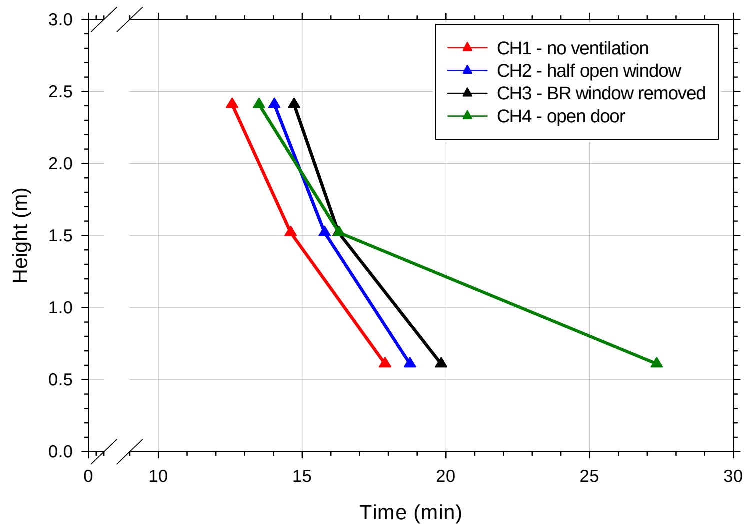
a. Living room



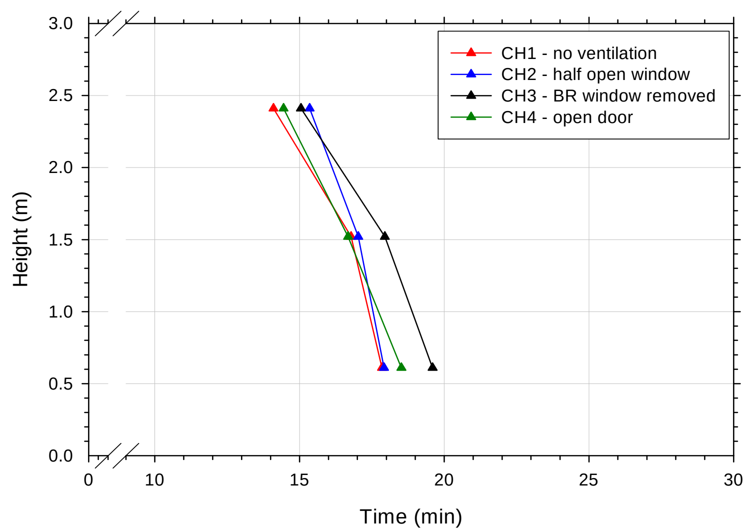
b. Bedroom

Figure 6-9. Time to 0.43 optical density per meter at sample elevations for low cabinet tests

Figure 6-10 shows a graphical representation of the time to target optical density in the high cabinet fire tests. As with the low cabinets, the tests generally reached the target optical density within approximately 2 minutes of each other. The exception to this being CH4, the open door test, where the layer did not descend to the 0.61 m (2 ft) location in the living room until much later in the test. The slopes in test CH1, CH2 and CH3 are very similar, showing that the layers in these tests developed similarly. The large difference in these tests is how the layers developed in the two difference rooms. In the living room, the layer descended from the 2.41 m elevation to the 1.52 m elevation quicker than from the 1.52 m elevation to the 0.61 m elevation. In the bedroom however, that is reversed.



a. Living room



b. Bedroom

Figure 6-10. Time to 0.43 optical density per meter at sample elevations for high cabinet tests

Generally, ventilation does not seem to have a profound effect on the progression of a smoke layer, as most locations reached the target optical density within one or two minutes of each other, which could be partially affected by the time variance in the tissue box ignition scenario, which was approximately 30 seconds. However, a difference can be noted in the open door ventilated cases. In the cabinet fire tests with the open door, the 0.43 m^{-1} smoke level at the 0.61 m (2 ft) elevation was reached much later than the other cabinet tests due to the slower descent of the upper layer. The larger ventilation opening caused a more distinct lower layer and delayed descent of the layer interface below the mid-room height.

7 TENABILITY ANALYSIS

A tenability analysis was performed for all tests. Tenability was determined at two characteristic elevations throughout the enclosure, 0.61 m (2 ft) and 1.52 m (5 ft). These elevations generally represent head-level height of an occupant crawling or walking, respectively. Three tenability factors were analyzed for these tests: temperature, floor level heat flux, and CO Fractional Effective Dose (FED). Tenability thresholds were determined using the criteria from ISO (ISO/DTS 13571, 2001) as shown in Table 7-1.

Table 7-1. Tenability Thresholds

Tenability Factor	Threshold Criteria
CO FED	0.3
	1
Heat Flux	2.5 kW/m^2
Temperature	120° C

The heat flux and temperature thresholds are both given as the threshold of pain and burns. Thermally untenable conditions are generally considered to be reached when temperatures exceed the threshold of 120°C (ISO/DTS 13571, 2001; Purser, 2002). At this temperature, a relatively short duration exposure can result in skin burn and the potential incapacitation of an occupant. Purser reports the tolerance time for exposure to 120°C as being seven minutes (Purser, 2002). Below a heat flux of 2.5 kW/m^2, a person can tolerate the heat for 30 minutes or more without much impact on escape (ISO/DTS 13571, 2001).

Untenable toxic gas conditions, particularly with respect to the presence of carbon monoxide (CO), can be determined using the product of transient gas concentrations and exposure duration, also known as a dose. A fractional effective dose (FED) can be calculated by normalizing the measured dose of CO with an empirical value of 35,000 ppm-min, determined to be lethal in experimental studies (ISO/DTS 13571, 2001; Kaplan et al., 1985).

The values for CO FED of 0.3 and 1.0 are given by ISO/DTS 13571 as values that would incapacitate approximately 11% and 50% of the exposed population, respectively. Until recently with the publication of ISO 13751, most studies have used an FED criteria of 1 as the incapacitating dose. Consequently, relative to the literature, the criteria of 0.3 is considered to be a conservative tenability limit. The CO FED was determined for the experimental data using the following equation:

$$FED = \sum \frac{[CO]}{35000\ ppm * min} \Delta t$$

where
[CO]is the average concentration of CO (ppm) over the time increment, Δt
$\Delta t$is the time increment (min).

Table 7-2 shows an overview of the tenability analysis performed over all tests. The table displays the time to untenable conditions for each tenability threshold. The FED for CO calculation assumes that an occupant is in the room for which the calculation is performed for the entire duration. Consequently, this analysis does not take into account the exposure a person would experience if moving from room to room. For example, if the threshold FED is not reached in the bedroom, but only in the living room, then a person in the bedroom would be expected to be able to escape even if briefly moving through the living room.

7.1 Test Conditions

The following plots show the time history of the measurements affecting tenability conditions for each test. Data is not presented for tests if untenable conditions were not reached. Based on the plots below and Table 1-2, there was negligible temperature rise and negligible reduction in oxygen in the smoldering tests (SM1 to SM4). In the smoldering cotton batting (SM1) and the smoldering sofa (SM4) tests, there was a notable increase in CO and smoke. However, in contrast to the smoldering fires, the flaming fires (S1, CH1 and CH2) produced the most hazardous fire conditions. These flaming fires produced elevated temperatures, with two of them exceeding the tenable threshold of 120°C. Oxygen concentrations were reduced to about 14 to 15 percent along the path of egress and CO levels exceeded FED values of one, indicating lethal exposures for most people.

In test SM2 (as in SM3), the sofa did not develop a self-sustaining smoldering fire. Instead, the polyurethane foam in the sofa only pyrolized to a small diameter around the cartridge heater where the radiant heat was sufficient to affect it. Consequently, the conditions within the enclosure were quite benign as indicated in Table 1-2. The older, used sofa burned in SM4 achieved self-sustaining smolder and produced CO with a limited hazard (presented below) over the nearly two hour test. As indicated below, the smoldering cotton batting produced the greatest CO hazard, but this should be considered relative to the test setup. Since sustained smoldering was not achieved with a comforter, cotton batting was used as a bounding source for bedding, since it has been established in prior works as a reliable medium for obtaining self-sustaining smolder with significant carbon monoxide production. In order to have a test that would last multiple hours, a large quantity of cotton batting (36 m^2 (384 ft^2)) was used and folded into a thick pile. It is expected that this source material and configuration may bound many actual bedding products in ease of smolder, duration of smolder and CO production.

Table 7-2. Time (min) to Untenable Conditions

		Smoldering Cotton Batting (SM1)	Smoldering Sofa 1 (SM2)	Smoldering Sofa 2 (SM3)	Smoldering Sofa 3 (SM4)	Sofa Closed (S1)	Sofa Full Open Window (S2)*	Sofa Half Open Window (S3)	Sofa Gas Half Open Window (S4)	Low Cabinet Closed (CL1)	Low Cabinet Half Open Window (CL2)	Low Cabinet Open Door (CL3)*	High Cabinet Closed (CH1)	High Cabinet Half Open Window (CH2)	High Cabinet No BR Window (CH3)**	High Cabinet Open Door (CH4)*
Temperature ($\geq 120^{o}$ C)	LR 0.61 m	N	N	N	N	N	N	14.8	N	N	N	N	N	N	N	N
	LR 1.52 m	N	N	N	N	14.0	13.6	13.2	1.2	18.2	18.0	21.4	N	N	22.5	25.5
	DR 0.61 m	N	N	N	N	N	N	14.9	N	N	N	24.2	N	N	N	27.1
	DR 1.52 m	N	N	N	N	15.1	14.5	13.9	1.4	17.7	17.8	17.3	21.4	N	22.1	20.6
	BR 0.61 m	N	N	N	N	N	N	15.5	N	N	N	N	N	N	N	N
	BR 1.52 m	N	N	N	N	N	15.7	14.8	3.1	N	63.6	24.6	N	N	N	26.8
Heat Flux ($\geq 2.5kw/m^2$)	LR (floor)	N	N	N	N	N	15.4	14.5	N	N	N	N	N	N	N	27.4
	DR (floor)	N	N	N	N	N	15.7	N	N	N	N	16.6	N	N	N	20.8
	BR (floor)	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
FED = 0.3	LR 0.61 m	97.5	N	N	N	22.7	N	16.2	7.7	23.5	25.3	N	20.6	21.1	23.2	N
	LR 1.52 m	95.8	N	N	103.7	19.4	16.0	15.0	7.4	18.7	19.6	18.4	17.5	17.7	19.3	20.6
	DR 1.52 m	79.2	N	N	N/A	22.0	16.3	15.2	6.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	BR 0.61 m	82.5	N	N	N	22.5	N	16.4	8.9	22.6	23.5	N	21.1	21.0	23.2	25.7
	BR 1.52 m	85.1	N	N	N	21.3	N	15.6	N/A	21.4	21.1	21.2	19.1	19.7	20.7	20.3
FED = 1.0	LR 0.61 m	126.3	N	N	N	35.1	N	20.4	18.5	33.0	37.7	N	22.9	23.6	N	N
	LR 1.52 m	115.5	N	N	N	27.6	N	16.9	15.7	24.3	25.1	28.5	18.8	19.3	20.6	23.1
	DR 1.52 m	113.5	N	N	N/A	36.5	N	18.3	17.4	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	BR 0.61 m	116.3	N	N	N	34.8	N	20.3	21.0	31.0	32.0	N	23.8	23.7	N	N
	BR 1.52 m	109.0	N	N	N	30.3	N	17.4	N/A	29.0	28.6	N	21.5	22.4	23.5	24.0

* - Manual suppression used (at 15.9 min in S2, at 33.8 min. in CL3, and at 36.6 min. in CH4). Tests CL3 and CH4 were mostly finished burning at time of suppression.

** - Cabinets fell off of the false wall in test CH3 at 29.6 minutes. Analysis was discontinued at this time.

N – Untenable conditions not reached before tests ended

N/A – Measurement not available in test

Figure 7-1 shows the CO concentrations for test SM1, the smoldering cotton batting test. The CO concentrations were greater at the 1.52 m (5 ft) than the 0.61 m (2 ft) location. The concentrations were fairly uniform throughout the enclosure at a given elevation. The CO concentration took approximately 170 minutes to reach its maximum value at any given location. The CO tenability threshold was exceeded due to prolonged exposure to moderate concentrations for multiple hours. CO was the only measured quantity that created a tenability concern during this test.

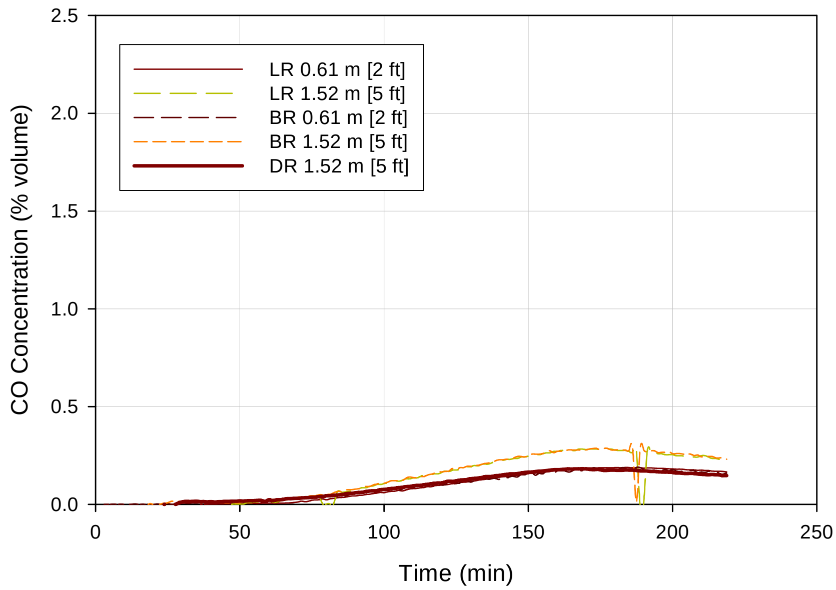


Figure 7-1. Test SM1 (smoldering cotton batting, no ventilation) CO concentrations

Figure 7-2 shows the CO concentrations for test SM4, the third smoldering sofa test. CO concentrations were relatively small during the entirety of the test (approximately 0.05% maximum at LR 1.52 m), only rising a small amount by the end of the test. Despite this small amount, tenability was compromised during the test due to the long extended exposure to CO. Only the lower (0.3 FED) dose threshold was reached and only close to the source (i.e., in the living room and not back in the bedroom). The smoldering polyurethane sofa presented a much lower and almost marginal hazard compared to smoldering cotton batting, which is likely a higher CO producing fuel configuration than even typical bedding.

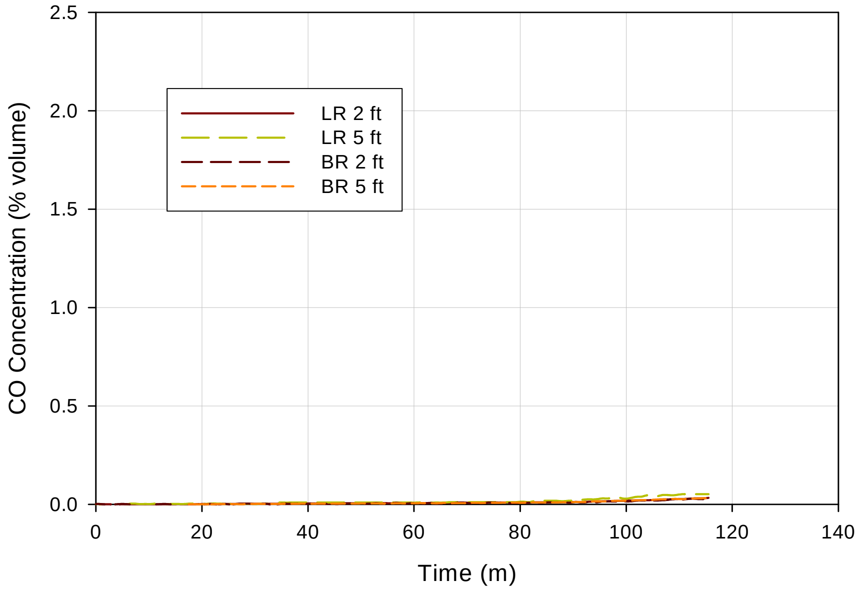
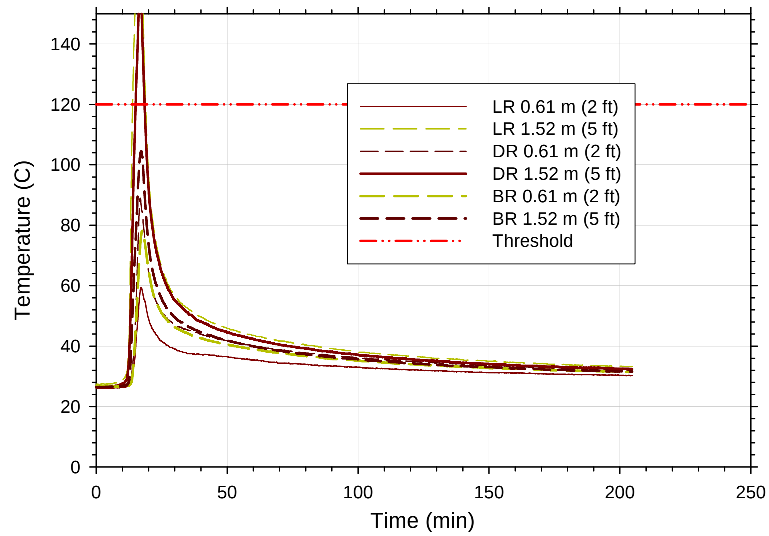


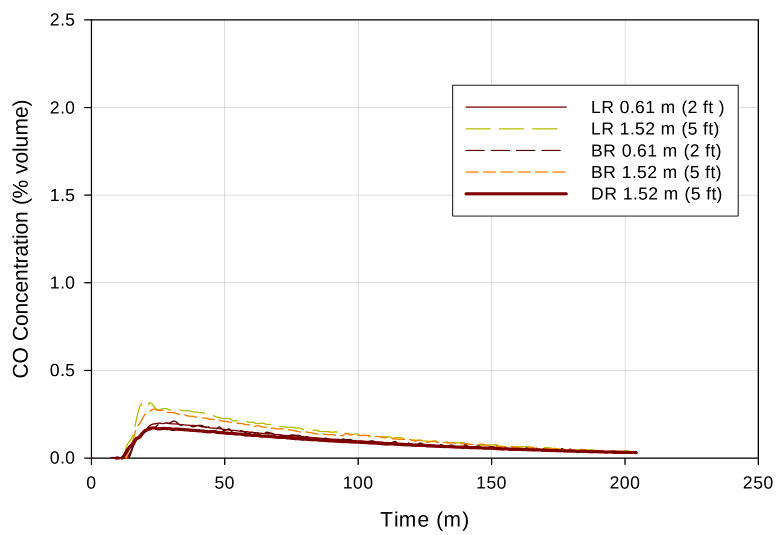
Figure 7-2. Test SM4 (smoldering sofa, no ventilation) CO concentrations

Figure 7-3 shows the temperature and CO concentrations for test S1, the no ventilation class A sofa test. Only the living room and dining room 1.52 m (5 ft) elevations exceeded the temperature threshold. The temperatures where very similar at these two locations. The temperature remained above the temperature threshold for approximately 4.8 minutes. Considering that Purser reports the tolerance time for exposure to 120^{o}C as being seven minutes [B] and that the bedroom temperature briefly reached a maximum less than 120^{o}C, this sofa fire with no ventilation could potentially be survivable relative to the thermal hazard. The CO concentrations reached a maximum of approximately 0.3%, at 1.52 m (5 ft) in the living room. The peak was relatively early in the test (~10 minutes after the sofa ignited), as compared to the smoldering tests which peaked late in the tests, about 2 hours after initiation. However, since the flaming sofa fire peaked early, the CO FED thresholds were reached in 20 to 35 minutes throughout the whole structure at which time the temperatures were quickly decreasing toward ambient conditions.

In this test, as well as in S3, the dining room CO and CO_2 levels were less than in the bedroom. Correspondingly, the O_2 concentrations in the dining room were higher than the bedroom. These results are contrary to those expected as the fire gases flowed from the living room to the bedroom and are contrary to the trends observed in tests S2 and S4. The data, analyzer sampling systems, and data acquisition systems were checked and no reasons for these unexpected trends in S1 and S3 were discovered.



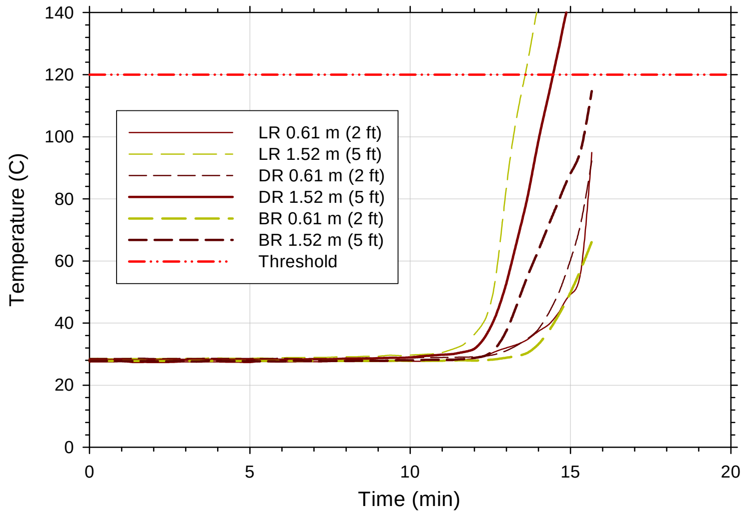
a) Temperature Tenability



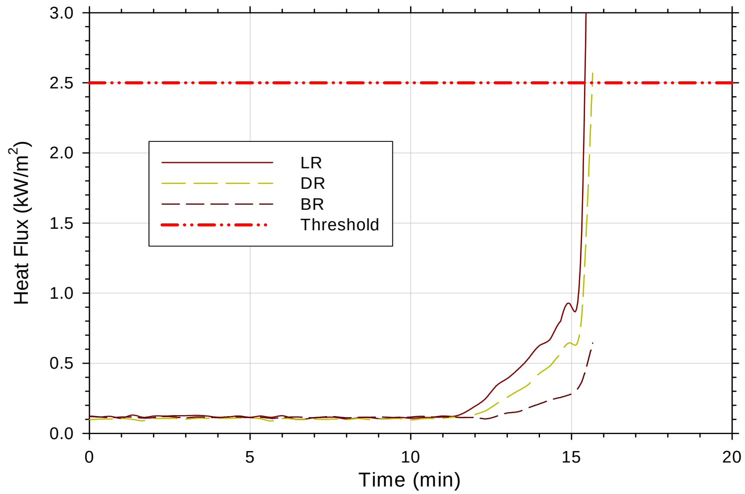
b) CO Concentrations Along Path of Egress

Figure 7-3. Test S1 (sofa, no ventilation) tenability data

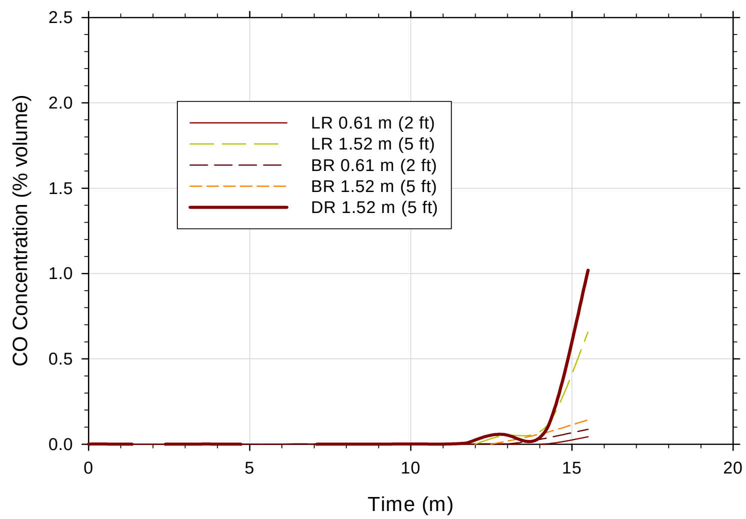
Figure 7-4 shows the tenability data for test S2, the full open window sofa test. This test was manually suppressed during the growth period. At the time of suppression, all temperatures were rising, with the living room and dining room 1.52 m (5 ft) elevations already exceeding the tenability threshold. All of the heat flux measurements were increasing as well; the dining room and living room locations had already exceeded the tenability criteria. The CO concentrations were also rising at the time of suppression. The living room and dining room 1.52 m (5 ft) locations increased the most rapidly of all locations.



a) Temperature Tenability



b) Heat Flux Tenability

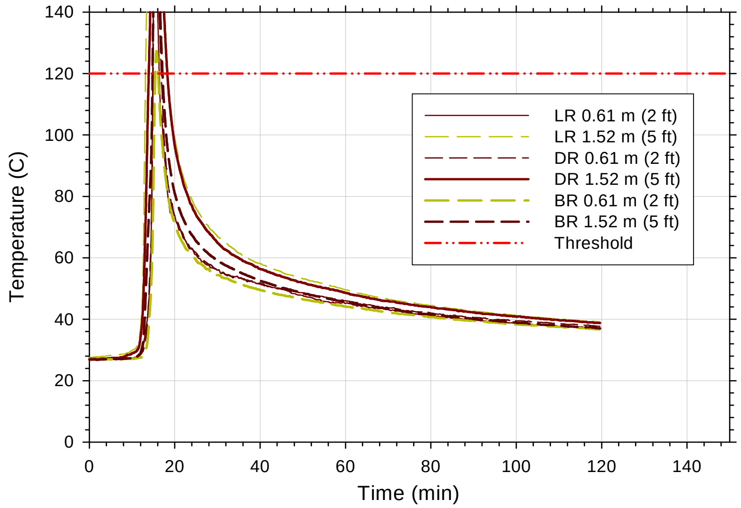


c) CO Concentrations Along Path of Egress

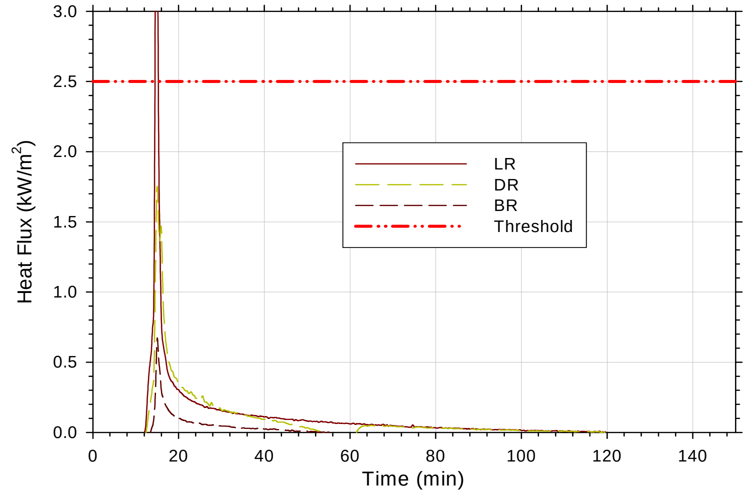
Figure 7-4. Test S2 (sofa, full open window) tenability data

Figure 7-5 shows the tenability data from test S3, the half open window class A sofa test. All of the sampled locations exceeded the temperature tenability criteria of 120°C, although the bedroom 0.61 m (2 ft) location barely reached this threshold. The 0.61 m (2 ft) location in the bedroom was above the threshold value for the shortest amount of time, approximately 0.7 minutes. The living room 1.52 (5 ft) location was above the threshold the longest, approximately 4.9 minutes. The living room was the only room to have a heat flux value that exceeded the tenability threshold of 2.5 kW/m^2, but it remained above the threshold for less than 1.8 minutes. The CO concentrations in this test increased sharply at approximately 12 minutes into the test. After peaking, the CO concentration began to decrease, and after approximately 20 minutes, the concentration had reached 50% of the peak value. As the fire became vitiated and burning ceased, CO production stopped and the CO in the enclosure decreased due to leakage.

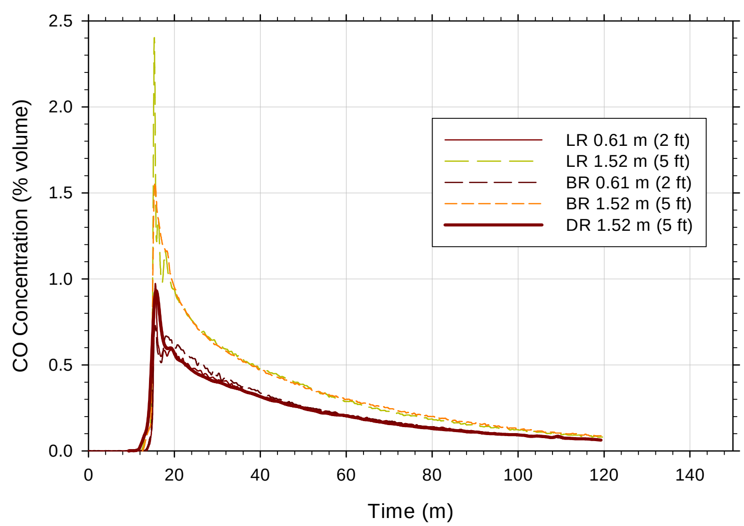
Figure 7-6 shows the tenability data for test S4, the half open window, gasoline-accelerated sofa test. Temperatures increased very quickly in all rooms. The living room and dining room 1.52 m (5 ft) locations exceed the temperature threshold and stayed above the threshold for approximately 3.5 minutes before falling after vitiation caused the fire to be suppressed. The bedroom 1.52 m (5 ft) location barely exceeded the temperature threshold, and remained above the threshold very briefly before decreasing. All other locations came close to the threshold but never reached it, with the exception being the 0.61 m (2 ft) location in the bedroom, which remained considerably cooler. The CO concentration also peaked shortly after ignition; the living room and dining room 1.52 m (5 ft) locations, where the highest concentrations were, reached a maximum value of approximately 0.3%.



a) Temperature Tenability

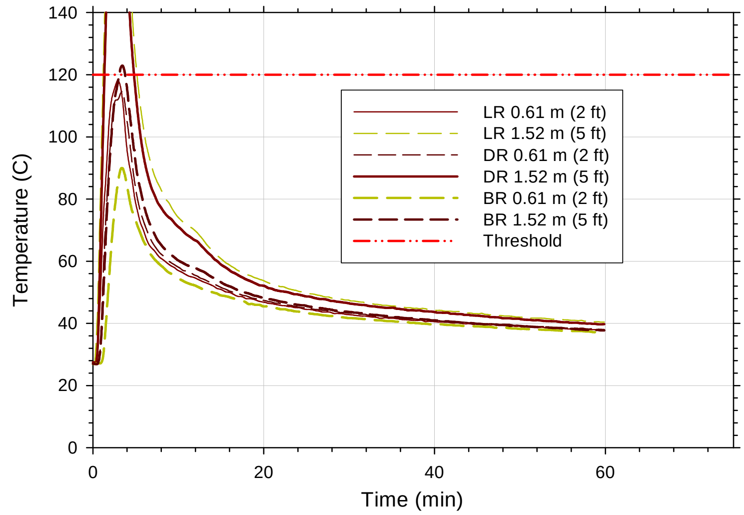


b) Heat Flux Tenability

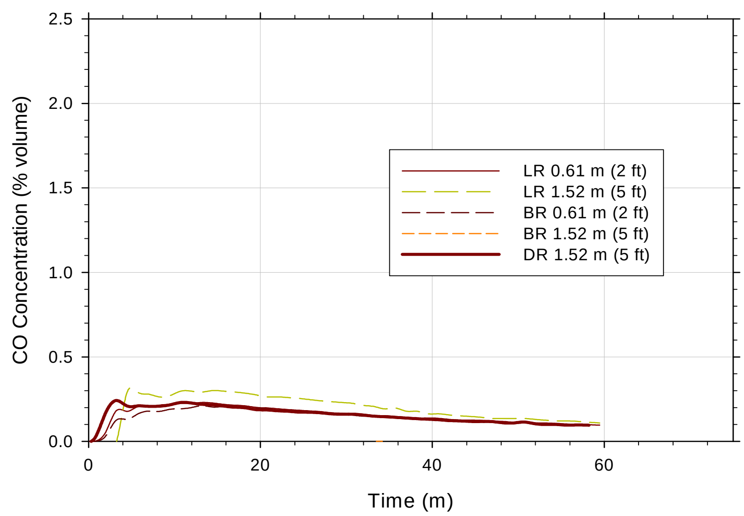


c) CO Concentrations Along Path of Egress

Figure 7-5. Test S3 (sofa, half open window) tenability data



a) Temperature Tenability



b) CO Concentrations Along Path of Egress

Figure 7-6. Test S4 (sofa, half open window, accelerated) tenability data

Figure 7-7 shows the tenability data for test CL1, the no ventilation low cabinet test. During the first temperature peak, the living room and dining room 1.52 m (5 ft) locations barely reached the tenability criteria. The temperatures at these location remained above the threshold for less than a minute. During the second peak, these two locations again surpassed the tenability threshold, but were still the only ones to do so. During this period, the temperatures remained above the threshold for approximately 3 minutes. The CO in the enclosure increased steeply at approximately 15-20 minutes, during the first peak burning, and then increased gradually, until the second peak burning at approximately 90-95 minutes, when it quickly increased again. Compared to the bedroom, the living room 1.52 m (5 ft) location had the largest concentration of CO throughout the test, with a maximum value of approximately 1.6%. In general, the kitchen fires led to worse conditions developing faster in the living room than in the bedroom. This was due to the large opening between the dining room and living room compared to the normal door way opening from the dining room to the bedroom (4.2 m^2 v. 1.8 m^2). The bedroom door soffit was also slightly lower than the soffit to the living room (0.41 m v. 0.31 m).

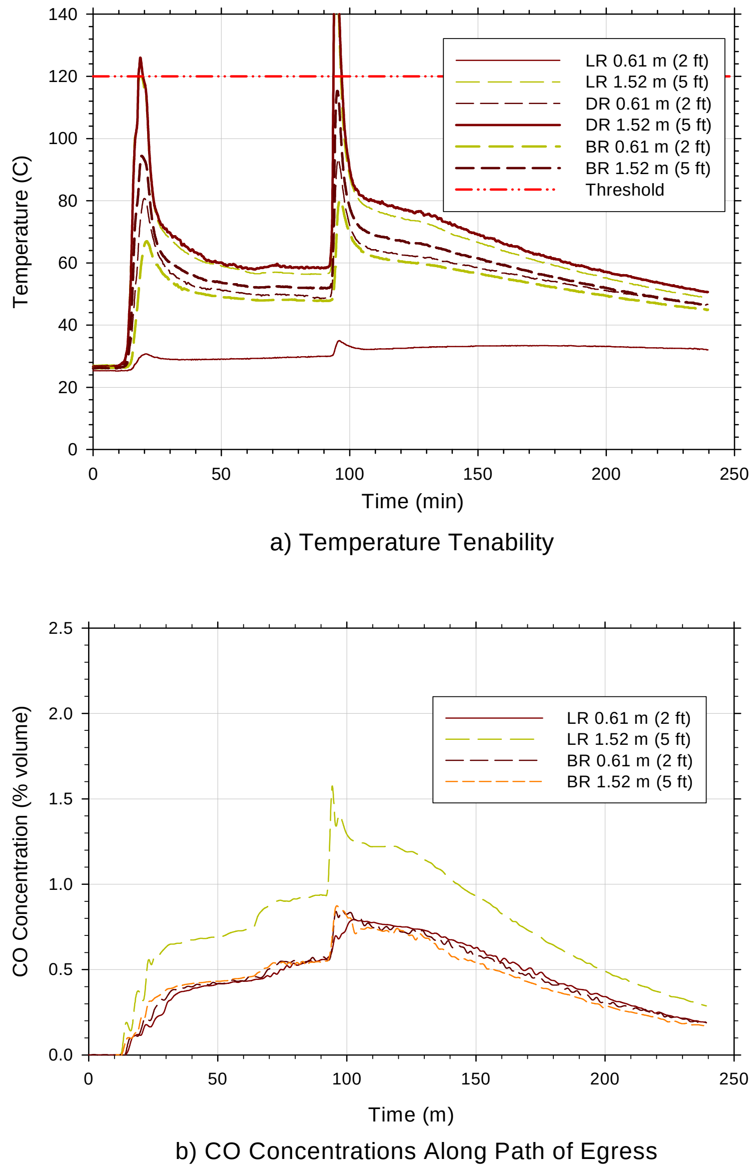
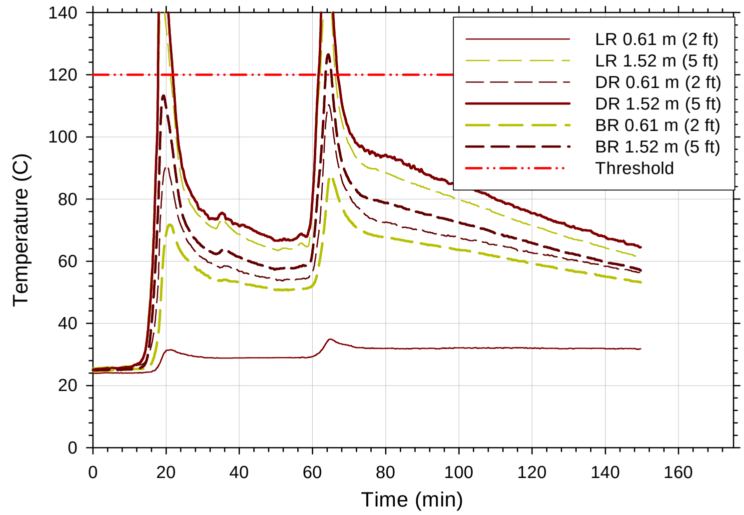
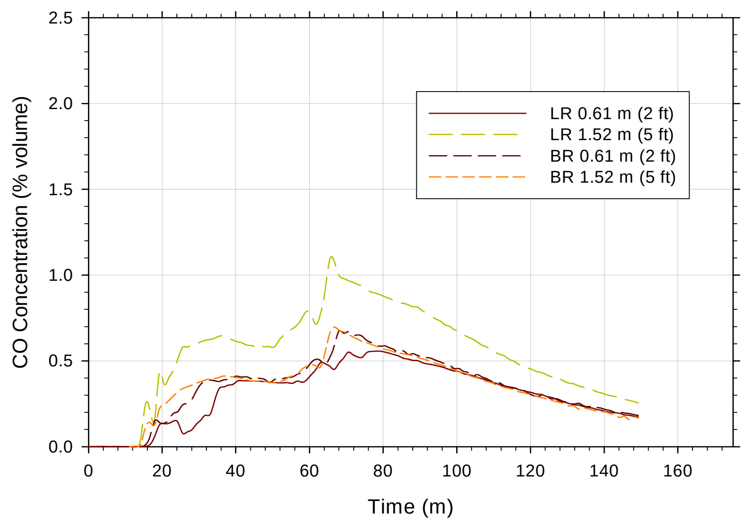


Figure 7-7. Test CL1 (low cabinet, no ventilation) tenability data

Figure 7-8 shows the tenability data for test CL2, the half open window, low cabinet test. During the first fire peak (at approximately 20 minutes), the temperature at the dining room and living room 1.52 m (5 ft) locations substantially exceeded the 120°C temperature threshold for tenability. During the second peak (at approximately 65 minutes), the 1.52 m (5 ft) location in the bedroom also exceeded the temperature threshold. As with the no ventilation scenario, the living room 0.61 m (2 ft) location showed very little temperature change. The CO concentration within the enclosure increased quickly during the first fire peak, then leveled off remained fairly constant until the second peak. The living room 1.52 m (5 ft) location again had a higher CO concentration than the bedroom, with a maximum value of approximately 1.1%.



a) Temperature Tenability



b) CO Concentrations Along Path of Egress

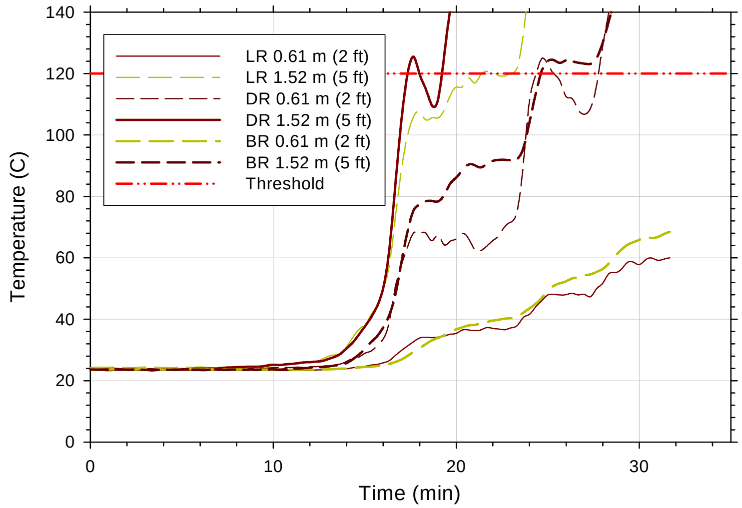
Figure 7-8. Test CL2 (low cabinets, half open window) tenability data

Figure 7-9 shows the tenability data for test CL3, the open door, low cabinet test. The dining room 1.52 m (5 ft) location barely crosses the temperature threshold during the first fire peak at approximately 17 minutes, and then substantially exceeds the threshold during the second burning peak at approximately 19 minutes as the second cabinet begins to burn. The living room 1.52 m (5 ft) location was the next to cross the threshold at approximately 21.5 minutes, although the temperatures do not increase beyond the threshold until approximately 23.5 minutes. The bedroom 1.52 m (5 ft) and dining room 0.61 m (2 ft) locations cross the threshold next, at approximately 24.5 minutes. Similar to the other kitchen cabinet fires, the bedroom conditions lag behind the dining room and living room.

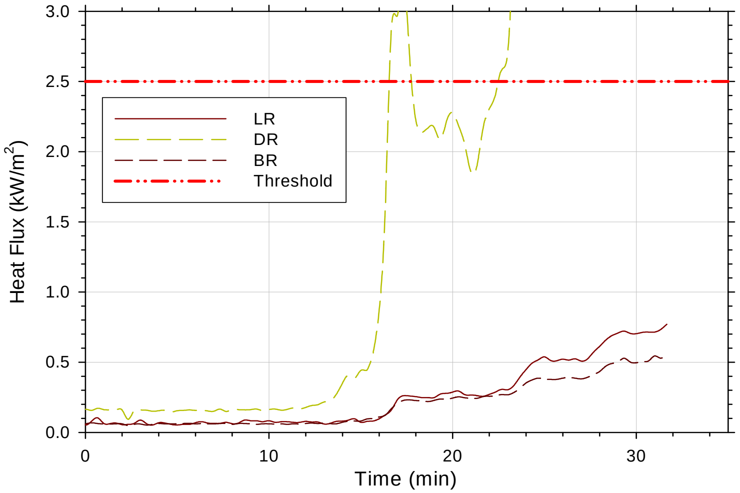
The living room and bedroom are not exposed to significant heat fluxes. However, the dining room would pose a short thermal threat to occupants trying to exit out the front door from the bedroom. The dining room heat flux exceeded the tenability threshold at approximately 16 minutes, during the initial fire growth period. It remained above the threshold for approximately 1.5 minutes and then fell below the threshold. The heat flux increased again at approximately 22 minutes and remained above the threshold until the end of the test.

The CO concentrations in the living room and bedroom at 1.52 m (5 ft) increased with multiple peaks during the test, with the living room increasing the most with a maximum value of approximately 0.8% at that location. The concentrations at the 0.61 m (2 ft) locations in both rooms did not change very much above ambient. Consistent with the low temperatures at the 0.61 m (2 ft) heights, the open door allowed fairly well defined layers with the lower layer staying tenable throughout the test until manually extinguished.

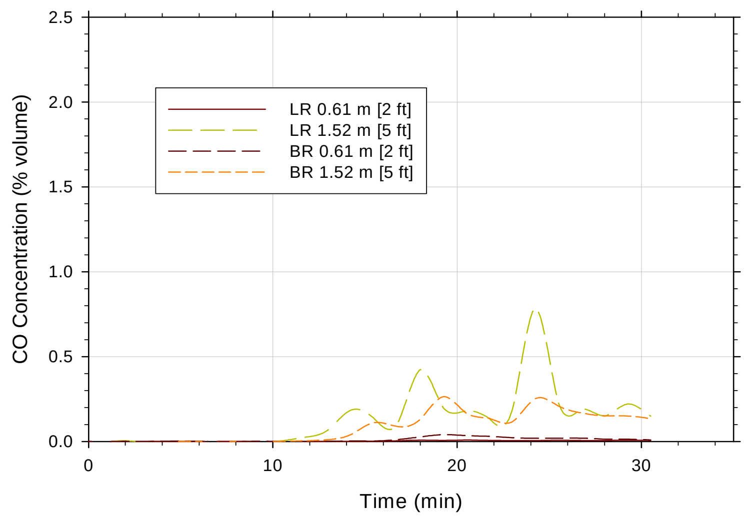
Figure 7-10 shows the tenability data for test CH1, the no ventilation, high cabinet test. Only the dining room 1.52 m (5 ft) location had a temperature rise above the tenability threshold; however, the duration was less than a minute. There were significant, rapid CO increases during this test, especially during the initial growth period, where the living room 1.52 m (5 ft) location had a CO concentration of approximately 2.1%, about twice as high as in the bedroom. The CO concentrations in the bedroom were uniform (high and low) and tracked closely with the 0.61 m (2 ft) level in the living room. This trend is similar to the temperature profiles.



a) Temperature Tenability

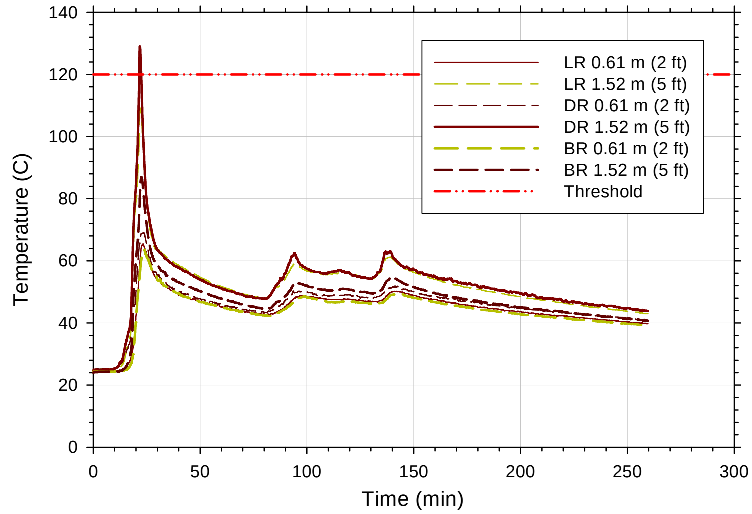


b) Heat Flux Tenability

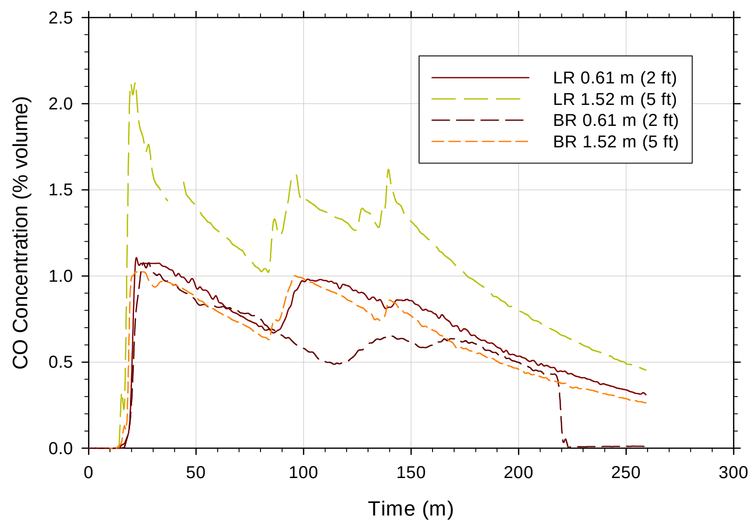


c) CO Concentrations Along Path of Egress

Figure 7-9. Test CL3 (low cabinets, open door) tenability data



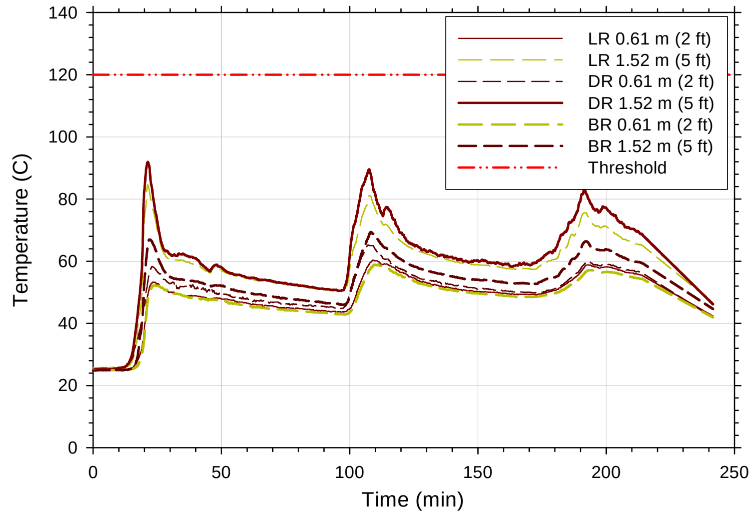
a) Temperature Tenability



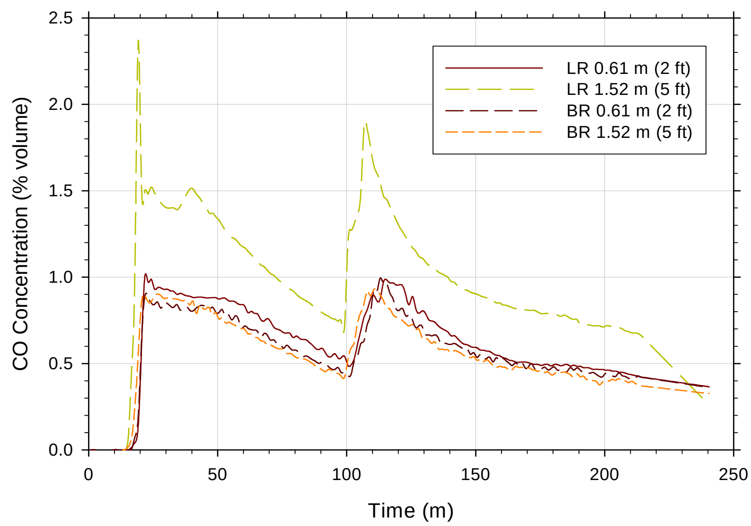
b) CO Concentrations Along Path of Egress

Figure 7-10. Test CH1 (high cabinets, no ventilation) tenability data

Figure 7-11 shows the tenability data for test CH2, the half open window, high cabinet test. During the test, no temperature rises beyond the tenability threshold were recorded. There were, however, some significant CO concentration increases similar to the no ventilation test (CH1). Again, the living room had the highest CO throughout the test, with a maximum value of approximately 2.4% during the initial growth phase. Similar to CH1, the temperature and CO levels in the bedroom were fairly uniform floor to ceiling and consistent with the lower layer living room values.



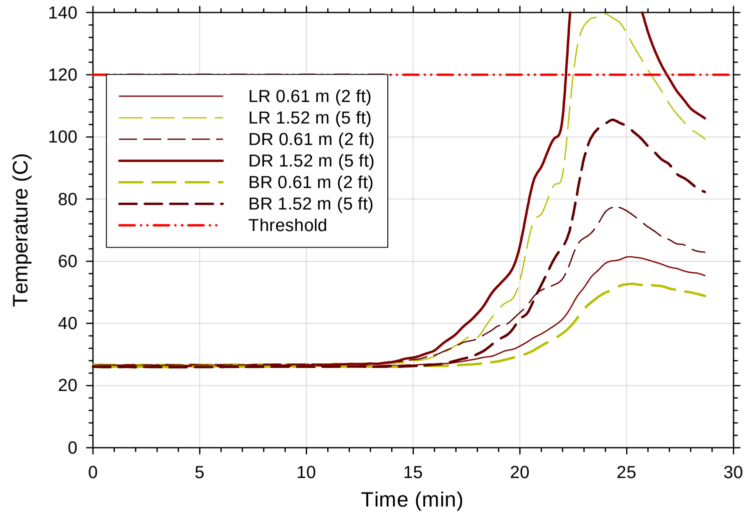
a) Temperature Tenability



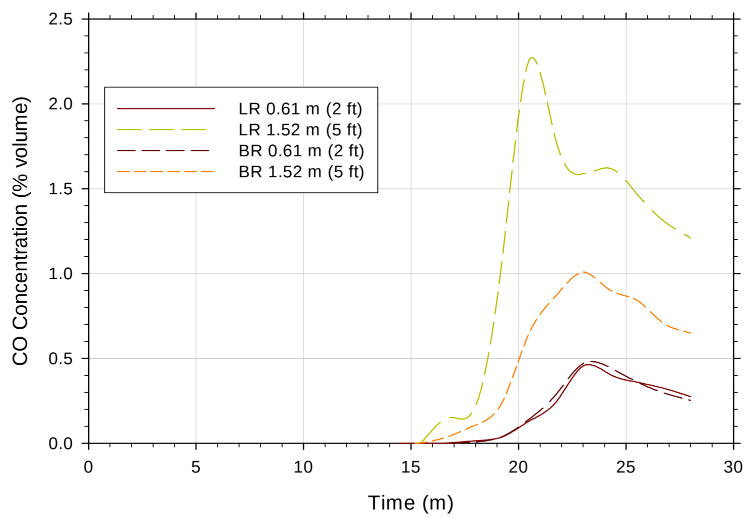
b) CO Concentrations Along Path of Egress

Figure 7-11. Test CH2 (high cabinets, half open window) tenability data

Figure 7-12 shows the tenability data for test CH3, the window removed, high cabinet test. The dining room and living room 1.52 m (5 ft) locations had a temperature rise above the tenability threshold at approximately 22 minutes. The living room location stayed above the threshold until approximately 26 minutes, and the dining room location was above the threshold until approximately 27 minutes as the fire became suppressed due to the vitiated environment. Similar to the other high cabinet tests, there was significant and rapid CO concentration rise in this test, especially in the living room at the 1.52 m (5 ft) location, which had a maximum value of approximately 2.3%. The bedroom 1.52 m (5 ft) location had the next highest concentration, though about half the peak value at 1%. CO levels declined as the fire became suppressed due to vitiated conditions.



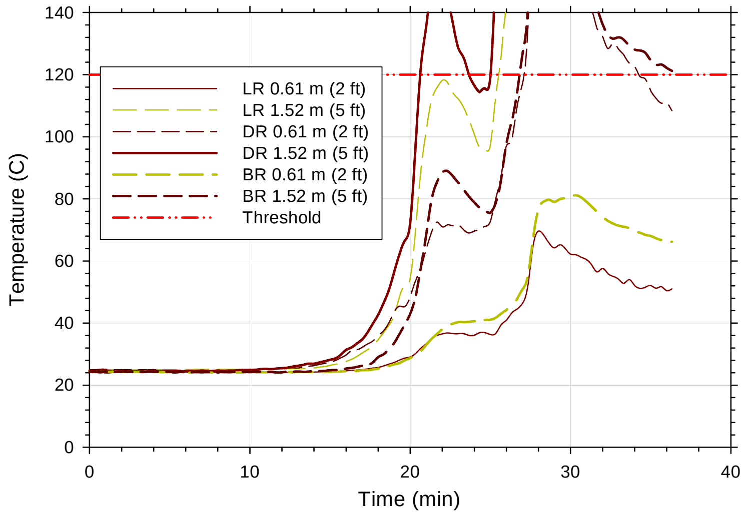
a) Temperature Tenability



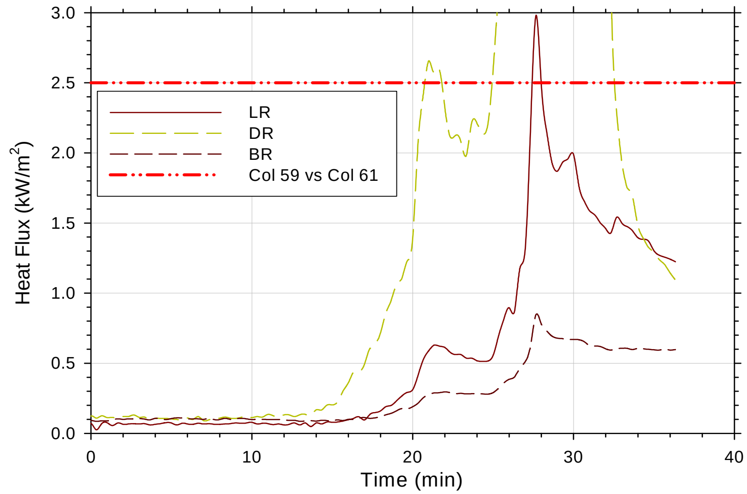
c) CO Concentrations Along Path of Egress

Figure 7-12. Test CH3 (high cabinets, BR window removed) tenability data

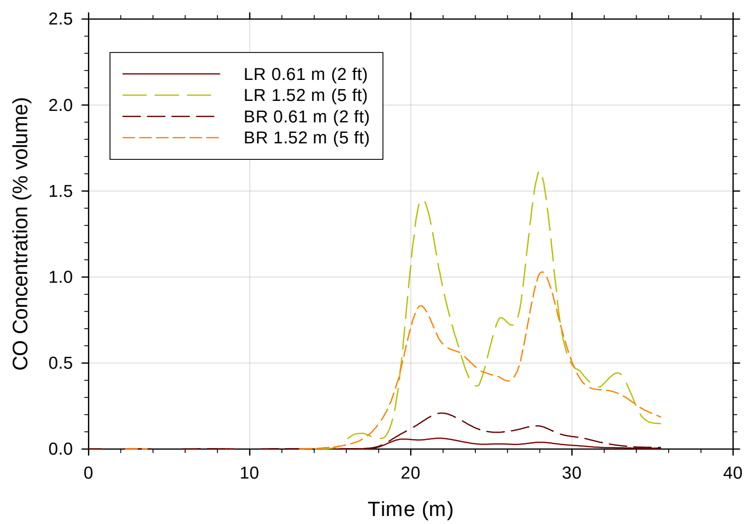
Figure 7-13 shows the tenability data for test CH4, the open door, high cabinet test. During the first burning peak, at approximately 20 minutes, the dining room 1.52 m (5 ft) location exceeded the temperature tenability threshold. This location remained above the threshold for approximately 2 minutes before slightly falling below the threshold and then rising again during the second burning peak. The threshold was passed at all locations within 27 minutes except at the 0.61 (2 ft) locations in the bedroom and living room, which remained at and below 80°C. The living room and dining room both experienced heat fluxes above the tenability threshold. There was also a sharp rise in the CO concentration as all four cabinets became involved and reached the first peak at about 21 minutes. The living room 1.52 m (5 ft) location again had the largest increase, reaching a maximum value of about 1.6%. The bedroom 1.52 m (5 ft) location had the next highest CO concentration, while the 0.61 m (2 ft) locations had a CO concentrations that did not exceed 0.25%.



a) Temperature Tenability



b) Heat Flux Tenability



c) CO Concentrations Along Path of Egress

Figure 7-13. Test CH4 (high cabinets, open door) tenability data

7.2 Impact of Ventilation

The ventilation provided to the fire can have a large effect on how quickly untenable conditions are reached (if at all). Comparisons of ventilation effects were performed using the class A ignition scenarios of each fuel source. A total of three scenarios for the sofa and low cabinets, and four scenarios for the high cabinets, were examined. For each scenario, the time to untenable conditions of temperature, CO FED, and heat flux were examined. Each comparison examined two locations within each scenario, the living room and bedroom at an elevation of 1.52 m (5 ft) for temperature and FED, and the at floor level for heat flux. Each section below presents details for each fire type. A full summary of the thermal and CO threats is provided in Table 7-3. Besides presenting the time to untenable thresholds, the table also presents the duration that the untenable temperature threshold was exceeded as well as the maximum gas temperature achieved. As noted earlier, Purser reports the tolerance time for exposure to 120^{o}C as being seven minutes (Purser, 2002).

7.2.1 Sofa Tests

Table 7-4 contains a brief overview of the times to untenable conditions for the sofa tests S1, S2, and S3. Figure 7-14 and Figure 7-15 show the temperature growth during the sofa fires in the living room and bedroom respectively. In the living room, which contained the fire, the tests all reached the temperature threshold of 120°C within one minute of each other, suggesting that the ventilation did not have a profound effect on the initial fire growth. In other words, there was sufficient oxygen in the closed apartment for the fire to become a limited thermal threat despite its relatively small size. As shown in Table 7-3 the temperature threshold was exceeded for less than 5 minutes in most scenarios. The amount of ventilation affected the thermal conditions to a greater extent further from the room of origin, with the partial ventilation tests reaching higher overall temperatures and heating up quicker than the no ventilation test (see Fig. 7-15). In the bedroom, the full and half open window ventilation scenarios reached the threshold approximately one minute apart from each other. The no ventilation scenario never reached the threshold in the bedroom.

Table 7-3. Thermal and CO Tenability at 1.52 m (5 ft)

		Thermal @1.52 m (5 ft) > 120°C									Time to CO FED @ 1.52 m (5ft)			
		LR			DR			BR			LR		BR	
Test	Description	Time reached (min)	Duration (min)	Peak Temp (C)	Time reached (min)	Duration (min)	Peak Temp (C)	Time reached (min)	Duration (min)	Peak Temp (C)	0.3 FED	1.0 FED	0.3 FED	1.0 FED
SM1	Smoldering Bedding	N			N			N			95.8	115.5	85.1	109.0
SM2	Smoldering Sofa 1	N			N			N			N	N	N	N
SM3	Smoldering Sofa 2	N			N			N			N	N	N	N
SM4	Smoldering Sofa 3	N			N			N			103.7	N	N	N
S1	closed	14.0	4.8	195.0	15.1	3.4	160.0	N			19.4	27.6	21.3	30.3
S3	half open window	13.2	5.1	428.0	13.9	4.3	316.0	14.8	2.3	179.0	15.0	16.9	15.6	17.4
S4	half open window accelerated	1.2	3.8	233.0	1.4	3.4	190.0	3.1	0.8	123.0	7.4	15.7	N/A	N/A
S2*	full open window	13.6	>2.3#	452**	14.5	>1.4#	289**	15.7	>0.2*	140**	16.0	N	N	N
CL1	closed	18.2 / 93.9	0.7 / 2.6	121 / 149	17.7 / 93.7	1.8 / 3.2	126 / 174	N			18.7	24.3	21.4	29.0
CL2	half open window	17.9 / 62.2	3.2 / 4.1	149 / 159	17.8 / 61.7	3.9 / 5.0	183 / 188	63.6	1.6	127.0	19.6	25.1	21.1	28.6
CL3*	open door	21.4	>10.4#	217.0	17.3	>14.5#	372.0	24.6	>7.2#	150.0	18.4	28.5	21.2	N
CH1	closed	N			21.4	1.0	129.0	N			17.5	18.8	19.1	21.5
CH2	half open window	N			N			N			17.7	19.3	19.7	22.4
CH3*	no window	22.5	>3.5#	140**	22.1	>4.8#	171**	N			19.3	20.6	20.7	23.5
CH4*	open door	25.5	>11.0#	269.0	20.6	>15.8#	548.0	26.8	>9.7#	183.0	20.6	23.1	20.3	24.0

N - Tenability threshold not reached
N/A - Sampling location not used in test due to analyzer malfunction
* - Test was manually suppressed.
** - Temperature was still rising when test was ended
# - Untenable conditions lasted until the end of the test

Table 7-4. Time (min) to Untenable Conditions for Sofa Tests

Tenability Factor	Location	Sofa No Ventilation (S1)	Sofa Half Open Window (S3)	Sofa Full Open Window (S2)*
Temperature ($\geq 120^{o}$ C)	LR 1.52 m (5 ft)	14.0	13.2	13.6
	BR 1.52 m (5 ft)	N	14.8	15.7
Heat Flux ($\geq 2.5 kw/m^2$)	LR (floor)	N	14.5	15.4
	BR (floor)	N	N	N
FED = 0.3	LR 1.52 m (5 ft)	19.4	15.0	16.0
	BR 1.52 m (5 ft)	21.3	15.6	N
FED = 1.0	LR 1.52 m (5 ft)	27.6	16.9	N
	BR 1.52 m (5 ft)	30.3	17.4	N

* - Manual suppression used at 15.9 min.
N - Not reached

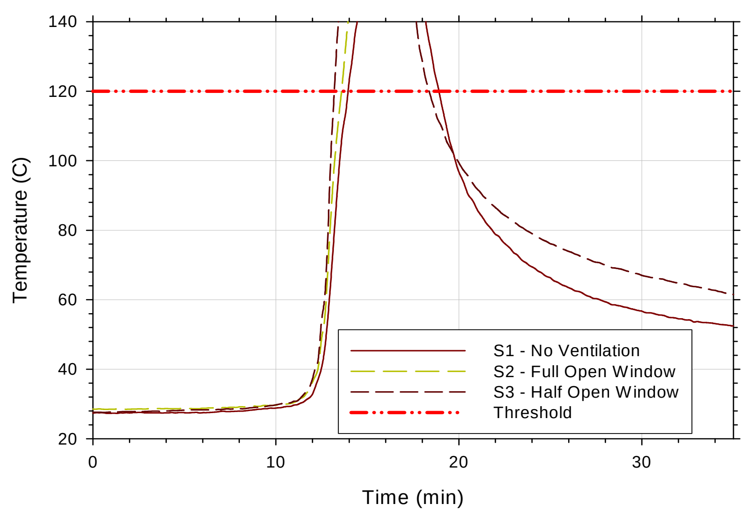


Figure 7-14. Temperature for sofa tests at 1.52 m (5 ft) in the living room (room of origin)

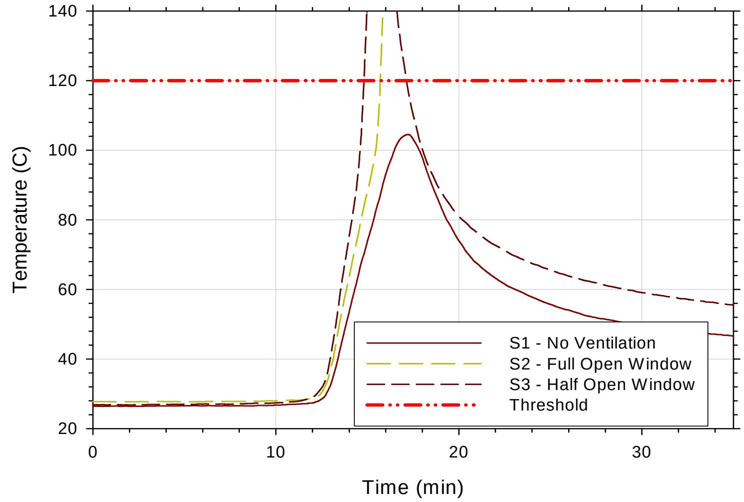


Figure 7-15. Temperature for sofa tests at 1.52 m (5 ft) in the bedroom

Figure 7-16 shows the heat flux data for sofa fires at the floor level in the living room. Tests S2 and S3 reached the untenable threshold of 2.5 kW/m^2 within one minute of one another. Test S1 never reached the threshold. This shows that with no ventilation, the sofa fire could not grow large enough to become untenable from the heat flux perspective. Test S1 reached a peak heat release rate less than 400 kW, where as tests S2 and S3 were above 800 kW.

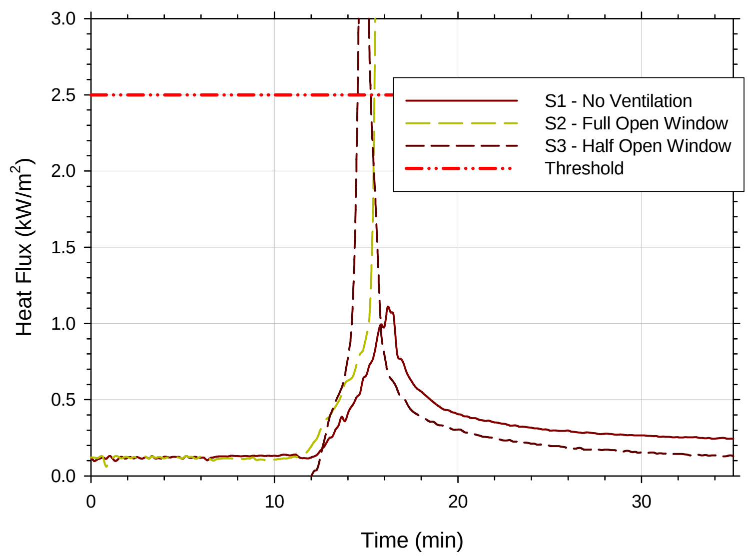


Figure 7-16. Heat flux for sofa tests at floor level in the living room

Figure 7-17 and Figure 7-18 show the sofa fire carbon monoxide tenability data in the living room and bedroom respectively. In the living room, the half open and full open window fires reached the 0.3 FED threshold within 1 minute of each other. The no ventilation scenario reached the threshold about 4 minutes later. Similarly for the 1.0 FED threshold, the no ventilation fire reached the threshold approximately 11 minutes later than the half open window (the full open window data is not available since the fire was manually suppressed before peak conditions were achieved). In the bedroom, increasing the ventilation had a larger effect on times to untenable conditions than in the living room. The half open window reached the 0.3 FED threshold about 5 minutes before the no ventilation scenario. The 1.0 FED threshold was reached in the bedroom by the half open window approximately 13 minutes before the no ventilation test. This data shows that a sofa fire with no ventilation can take longer to reach untenable conditions than a fire with even a small amount of ventilation. This is due primarily because the additional ventilation allows the fire to grow larger and produce a higher peak level of CO before becoming suppressed due to vitiated conditions. After the sofa fires peaked due to vitiation, there was no further loss of fuel mass or generation of carbon monoxide.

The CO FED results (as compared in Table 7-3) show how proximity to the area of origin can have an impact on occupant safety for spaces with no ventilation. Even for this relatively small apartment dwelling, CO concentrations in the remote bedroom increased slower than in the living room, resulting in longer times to untenable FED levels, approximately 2 to 3 minutes. With just a small amount of ventilation, such as a half open window (test S3), there was increased transport of gases within the apartment resulting in less than 1 minute delay between the bedroom and living room, which is less than half that for the closed compartment. For a flaming fire, an extra one to two minutes can make a difference of survival.

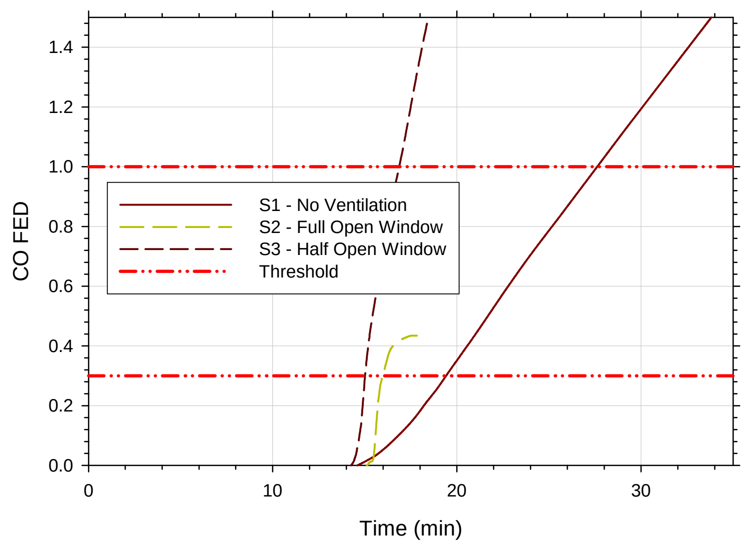


Figure 7-17. CO FED for sofa tests at 1.52 m (5 ft) in the living room.

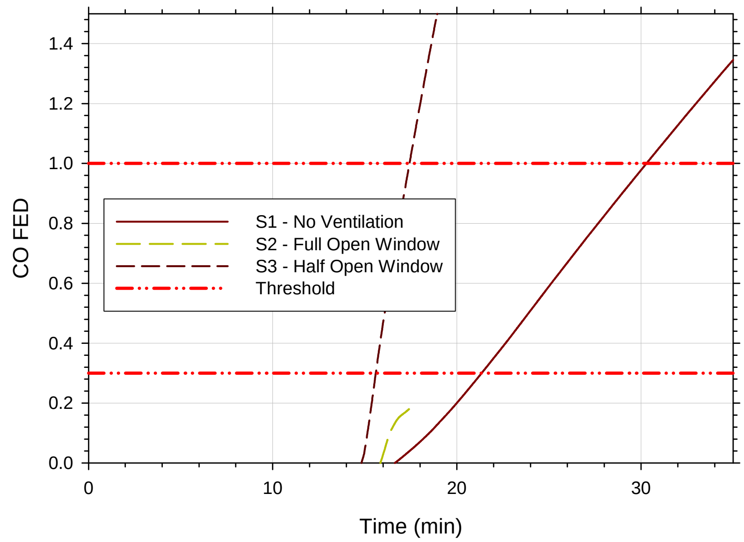


Figure 7-18. CO FED for sofa tests at 1.52 m (5 ft) in the bedroom

Overall, for sofa fires, a fire with no ventilation will remain tenable for longer than a fire with some ventilation, particularly farther from the room of origin. Even relatively small ventilation, such as the half open window, can make a large difference in the time to both thermal and toxic gas untenable conditions. The change from the full open to half open window did not make a notable difference in the time to untenable conditions when compared to the difference between little and no ventilation (i.e. half open window to no ventilation). However, as the ventilation area is increased, there will be a minimum threshold area that will allow the fire to continue to burn.

7.2.2 Low Cabinet Tests

Table 7-5 contains a brief overview of the time to untenable conditions for the low cabinet tests. Figure 7-19 and Figure 7-20 show the temperature data in the living room and bedroom from low cabinet tests. In the living room, the no ventilation and half open window tests reached untenable temperature conditions within one minute of one another. However, as can be seen in Figure 7-19 and Figure 7-20 for CL1 with no ventilation, the fire barely reached the temperature tenability threshold of 120°C and actually decreased immediately (within a minute) as the fire became suppressed due to vitiation. The untenable temperature threshold was exceeded for a longer duration (3 minutes) in the test with the half open window. As noted with the sofa fires, increased ventilation also created a greater hazard with the low cabinet fires. In the open door test, the thermally untenable conditions persisted to the end of the test (> 10 min.) once they were achieved. Table 7-4 shows that the threshold in the living room was achieved for the open door test about three minutes later than the tests with less ventilation. The reason for this delay is that the open door in the living room prevented the hot (untenable layer) from descending as quickly as it did in the tests with no or minimum ventilation. As can be seen in Table 7-4, even though the layer took a few minutes longer to descend to 1.5 m in the living room for the open door test, the bedroom became untenable much faster than the fires with a half open window or no vent (25 min., 64 min., and never, respectively). In the bedroom, the half open window test did not exceed the threshold until the fire peaked a second time. The no ventilation scenario did not reach untenable temperature conditions in the bedroom; however, it came close (~116°C) during the second peak when the fire started to grow again about 76 minutes later.

Table 7-5. Time (min) to Untenable Conditions for Low Cabinet Tests

Tenability Factor	Location	Low Cabinet No Ventilation (CL1)	Low Cabinet Half Open Window (CL2)	Low Cabinet open Door (CL3)*
Temperature ($\geq 120^{o}$ C)	LR 1.52 m (5 ft)	18.2	18.0	21.4
	BR 1.52 m (5 ft)	N	63.6	24.6
Heat Flux ($\geq 2.5 kw/m^{2}$)	LR (floor)	N	N	N
	BR (floor)	N	N	N
FED = 0.3	LR 1.52 m (5 ft)	18.7	19.6	18.4
	BR 1.52 m (5 ft)	21.4	21.1	21.2
FED = 1.0	LR 1.52 m (5 ft)	24.3	25.1	28.5
	BR 1.52 m (5 ft)	29.0	28.6	N

* - Manual suppression used at 33.9 min.
N - Not reached

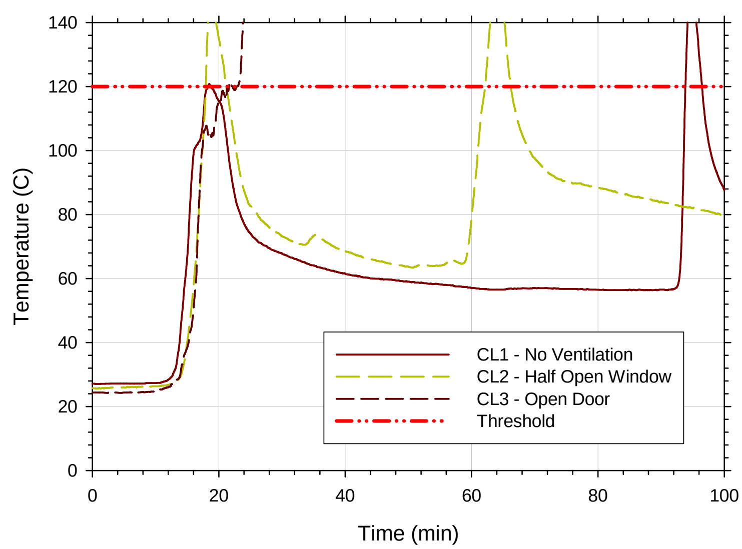


Figure 7-19. Temperature for low cabinet tests at 1.52 m (5 ft) in the living room

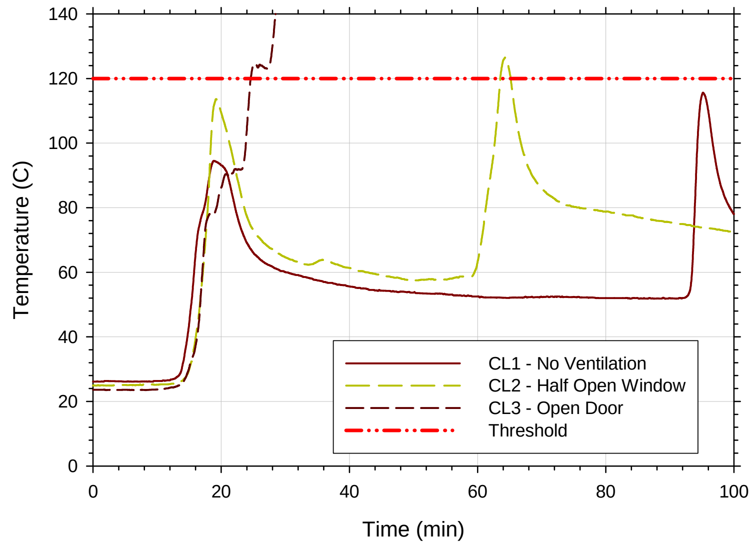


Figure 7-20. Temperature for low cabinet tests at 1.52 m (5 ft) in the bedroom

Figure 7-21 and Figure 7-22 show the carbon monoxide FED data for the living room and bedroom in low cabinet tests. In general, the times to untenable conditions were fairly close (within a minute) for all tests for both FED thresholds, except the open door test that reached the 1.0 FED threshold approximately four minutes after the other tests and did not reach the 1.0 FED level in the bedroom. As noted for the thermal tenability, the delay in the living room is partly attributed to the slower descending layer. However, the reduced CO threat for the open door test is also attributed to more complete combustion of the fuel with the greater ventilation. Figure 7-7, Figure 7-8, and

Figure 7-9 reinforce this finding, showing that test CL3 did not build up as high of a CO concentration as in tests CL1 and CL2. The CO FED results show that contrary to the sofa fires, the low cabinet fires with no ventilation produced about the same hazard as with limited ventilation. This may be due to the lower heat release rate of the wood cabinet fires compared to the sofa tests. Since the cabinet fires did not grow as rapidly as the sofa fires, there was sufficient air in the apartment enclosure to allow the fire to burn longer and to continue producing CO even with no ventilation. Where as in the sofa fires, the fires grew very quickly, resulting in CO production only during the rapid growth to the peak at which point the fire was suppressed due to lack of sufficient oxygen. Consequently, the sofa fires were more sensitive to ventilation for producing a peak CO level after which reaching untenable FED levels was only a function of time.

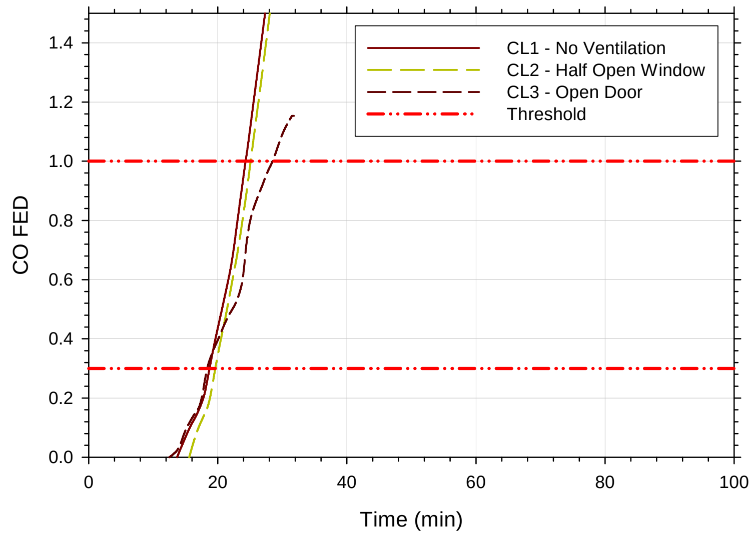


Figure 7-21. CO FED for low cabinet tests at 1.52 m (5 ft) in the living room

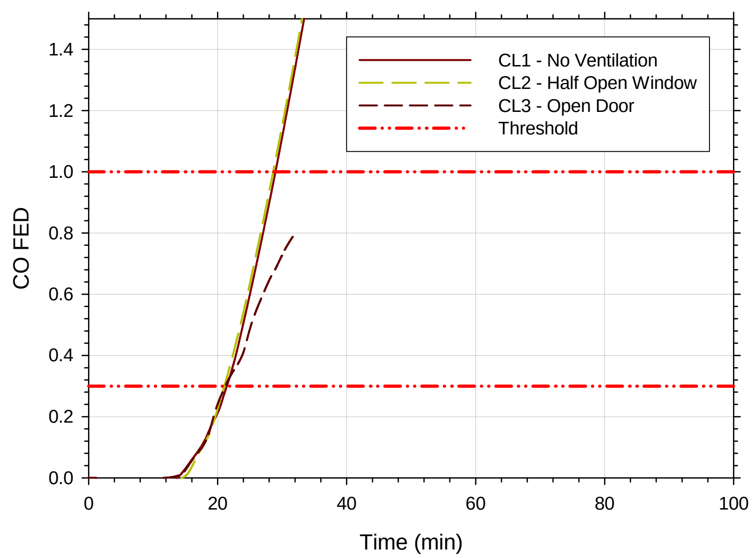


Figure 7-22. CO FED for low cabinet tests at 1.52 m (5 ft) in the bedroom

7.2.3 High Cabinet Tests

Tenability data from the high cabinet tests is presented below. Table 7-6 contains a summary of the times to untenable conditions for the high cabinet tests. Figure 7-23 and Figure 7-24 show the temperature tenability data for high cabinet fires. In the living room, the test with the bedroom window removed reached the temperature threshold first, followed about three minutes later by the open door test. The no ventilation and half open window tests did not reach the temperature threshold. Although the removed window vent test reached an untenable temperature in the living room first, this smaller ventilation opening actually yielded less dangerous thermal conditions overall compared to the open door test. As seen in Figure 7-23 and Figure 7-24, the open door test produced hotter temperatures and exceeded the tenability threshold for a longer period of time in both the living room and bedroom. The removed window test did not achieve untenable conditions in the bedroom at the point cabinets fell and the test was terminated (~30 min.).

Table 7-6. Time (min) to Untenable Conditions for High Cabinet Tests

Tenability Factor	Location	High Cabinet No Ventilation (CH1)	High Cabinet Half Open Window (CH2)	High Cabinet No BR Window (CH3)*	High Cabinet Open Door (CH4)**
Temperature ($\geq 120^{o}$ C)	LR 1.52 m (5 ft)	N	N	22.5	25.5
	BR 1.52 m (5 ft)	N	N	N	26.8
Heat Flux ($\geq 2.5 kw/m^2$)	LR (floor)	N	N	N	27.4
	BR (floor)	N	N	N	N
FED = 0.3	LR 1.52 m (5 ft)	17.5	17.7	19.3	20.6
	BR 1.52 m (5 ft)	19.1	19.7	20.7	20.3
FED = 1.0	LR 1.52 m (5 ft)	18.8	19.3	20.6	23.1
	BR 1.52 m (5 ft)	21.5	22.4	23.5	24.0

* - Cabinets fell off of wall at 29.6 min
** – Manual suppression used at 36.6 min
N – Not reached

The no ventilation and half open window tests also did not reach the temperature tenability threshold in the bedroom. Therefore, as noted with the low cabinet fires, an increase in ventilation correlates to higher temperatures and longer sustained untenable conditions, and under a certain ventilation size, for these tests between the half open window and window removed (0.12 to 0.67 m^2), the fire cannot grow large enough to become thermally untenable.

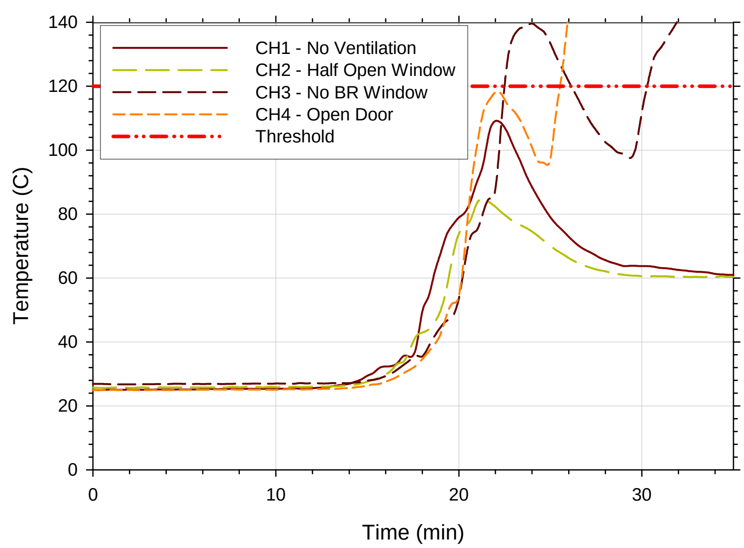


Figure 7-23. Temperature for high cabinet fires at 1.52 m (5 ft) in the living room

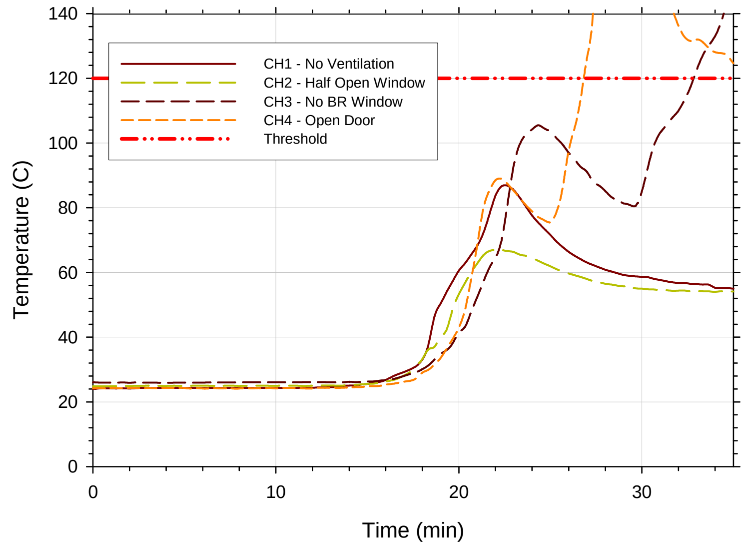


Figure 7-24. Temperature for high cabinet fires at 1.52 m (5 ft) in the bedroom.

Figure 7-25 and Figure 7-26 show the heat flux tenability data for high cabinet fires. Only the open door test reached the heat flux threshold of 2.5 kW/m^2. This threshold was maintained in the living room and dining room for approximately 2 and 8 minutes, respectively. In the dining room, the heat flux was sufficient (max of 13.3 kW/m^2) to ignite a crumpled piece of paper lying on the floor next to the heat flux gauge, but the carpet did not ignite.

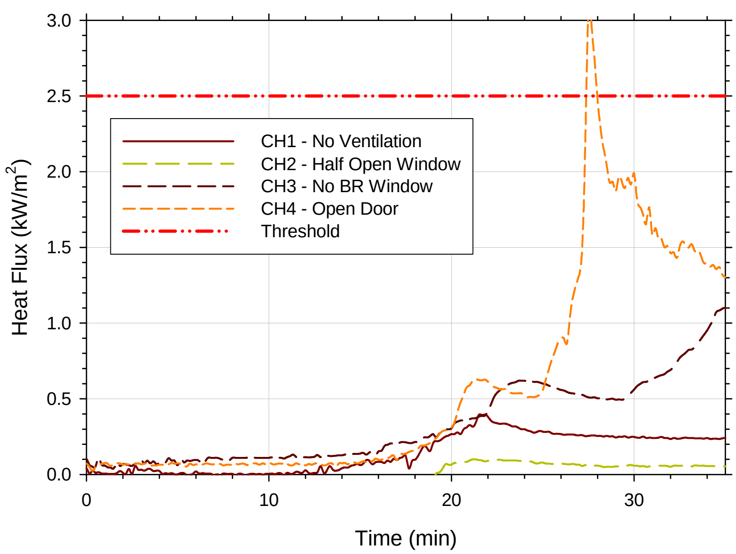


Figure 7-25. Heat flux for high cabinet fires at floor level in the living room

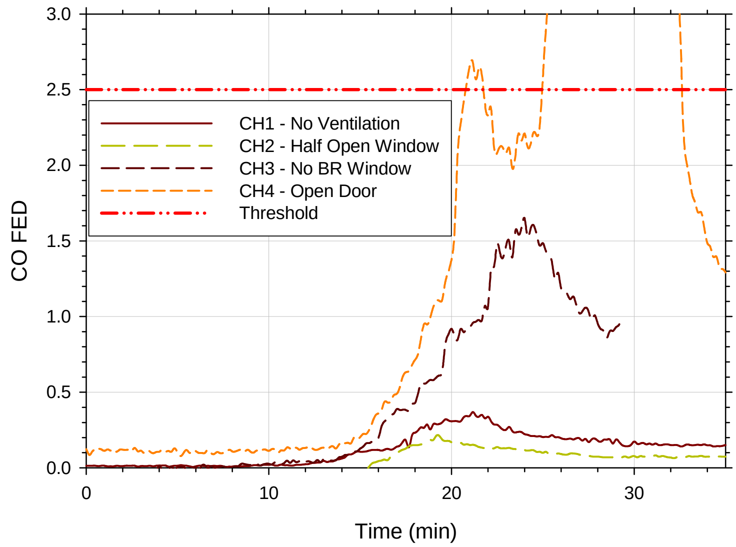


Figure 7-26. Heat flux for high cabinet fires at floor level in the dining room

Figure 7-27 and Figure 7-28 show the carbon monoxide FED data for high cabinet tests. In general, the tests reached the tenability thresholds in order according to amount of ventilation, (i.e. the less ventilation a test had, the quicker it reached the threshold) with one exception. In the bedroom, the open door and no window test switched order for the 0.3 FED threshold. However, the difference in times was small for all tests, generally within 1 to 2 minutes and no larger than 4 minutes. The larger increase of 4 minutes to untenable conditions relates to the living room CO levels in the open door test, which is attributed to the large vent present at the sampling location and the layer staying higher for a longer period of time than in the other tests, as well as reduced CO generation due to more air.

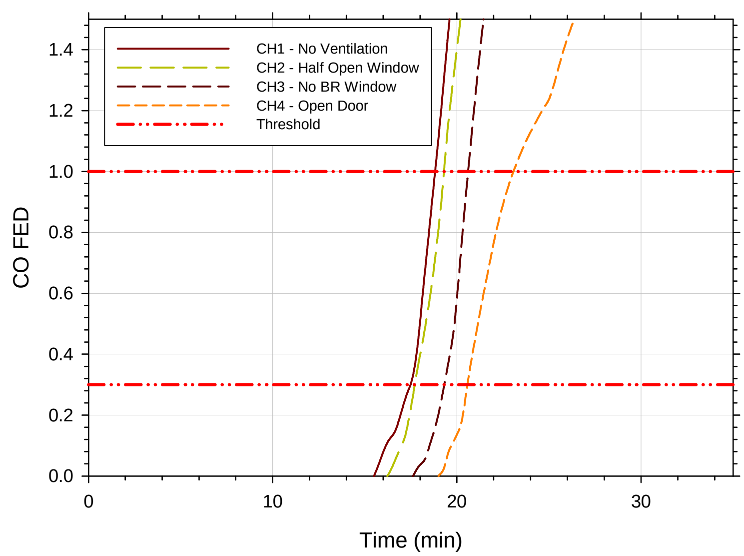


Figure 7-27. CO FED for high cabinet tests at 1.52 m (5 ft) in the living room

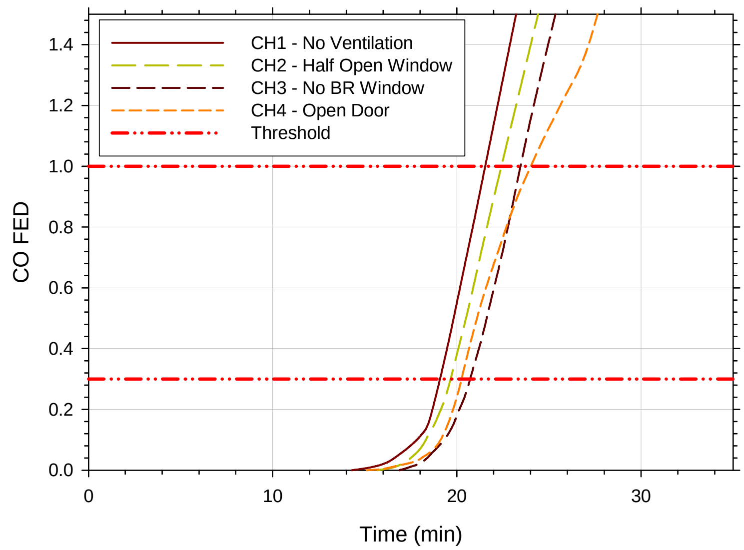


Figure 7-28. CO FED for high cabinet tests at 1.52 m (5 ft) in the bedroom

7.2.4 General Conclusions on Ventilation and Fuel Source Effects on Tenability

By examining Table 7-2 and the observations made above, some general conclusions can be made about the impact that ventilation had on tenability.

- Thermal hazards
  - Overall thermal hazards increase as ventilation increases.
  - Below a critical vent size, hazardous conditions will not be created throughout a dwelling.
  - For many tests where untenable temperatures were reached, they had similar times to untenable conditions.
  - Greater duration of untenable conditions occurred with increased ventilation.
  - Higher temperatures occurred with increased ventilation.
  - Sofa fires: Untenable temperatures (> 120°C) were reached in about 14 minutes and persisted for ~1 to 5 minutes with limited or no ventilation. Temperatures continually decreased after sofa fire was suppressed due to vitiated conditions.
  - Low cabinet fires: Untenable temperatures peaked multiple times over 1 to 1.5 hours with total durations above 120°C of 3 to 9 minutes for limited ventilation and greater than 10 minutes for open door tests.
  - High cabinet fires: Untenable temperatures were not a threat with limited ventilation (no ventilation or half open window), but with an open door or full window opening, untenable temperatures were reached in about 20-25 minutes and lasted for 5 to 10 minutes until the tests were terminated.

- CO hazard
  - Sofa fires:
    - With no ventilation, times to untenable criteria longer than with ventilation (~ 5 to 11 minutes difference depending on FED of 0.3 and 1, respectively).

    - Since the full open window was manually extinguished prematurely and larger ventilation scenarios could not be tested due to time constraints, there is limited data to establish clear trends for varying degrees of ventilation.
    - However, comparing no ventilation to any degree of ventilation showed that with ventilation, there was more of a CO hazard.
- Cabinet fires:
    - Overall, times to reach hazard were similar across all ventilations (~1 to 4 minutes across all ventilations, no ventilation to door open). There is a slight, but not always consistent, trend that CO untenability was reached slower with increasing ventilation (particularly for the high cabinet tests). Essentially, increasing ventilation created slightly less hazardous CO conditions for the high cabinet arrays. This is opposite the trend observed for sofa fires.

The following points highlight the tenability results as grouped and compared by fuel type relative to ventilation.

- Sofa fires posed a faster thermal hazard than the cabinet fires, resulting in shorter times to untenable temperatures (~14-15 min. v. ~18-27 min.) and higher peak temperatures. There was no consistent trend of whether sofa or cabinet fires developed untenable CO hazards quicker; it depended on ventilation and location of the cabinets (high or low in the space). All the fires produced lethal CO levels in about 15 to 30 minutes.
- In general, sofa fires became more hazardous with ventilation than without, sustaining untenable temperatures longer and reaching untenable CO exposures sooner.
    - With no ventilation, thermally untenable conditions were created before untenable CO levels in the living room and dining room, but remote from the fire in the bedroom, temperatures remained tenable and lethal levels of CO developed.
    - With ventilation, untenable temperatures were created about the same time or sooner than untenable CO conditions.
    - Lethal CO exposures were delayed with no ventilation compared to any amount of limited ventilation.

- In general, low kitchen cabinet fires became more hazardous with ventilation than without, sustaining untenable temperatures longer and reaching untenable CO exposures sooner.
    - With no ventilation, thermally untenable conditions were created before untenable CO levels in the living room and dining room, but remote from the fire in the bedroom, temperatures remained tenable and lethal levels of CO developed (similar to sofa fires).
    - With ventilation, untenable temperatures were created about the same time or sooner than untenable CO conditions (similar to sofa fires).

    - Lethal CO exposures were about the same with no ventilation compared to any amount of limited ventilation (contrary to sofa fires).

- In general, high kitchen cabinet fires became more hazardous with ventilation than without, reaching untenable temperatures, sustaining them longer and reaching untenable CO exposures about the same time.
    - With no ventilation or very limited ventilation (half open window), thermally untenable conditions were not created throughout the apartment, but lethal levels of CO developed throughout (thermal trends contrary to sofa fires, CO hazard comparable).
    - With or without ventilation, untenable temperatures were created after untenable CO conditions (contrary to sofa and low cabinet fires).
    - Lethal CO exposures were about the same or worse with no ventilation compared to any amount of limited ventilation (contrary to sofa fires).

- The reason that unventilated sofa fires had longer times to lethal CO levels (i.e., lower hazards) than limited ventilation fires while cabinet fires did not have this trend can be two fold. First, the unventilated sofa fire did not grow as large as the limited ventilation sofa fires before becoming vitiated and suppressed; and consequently, did not produce as much CO. Since the sofa fires stopped burning after becoming vitiated and no longer produced CO, the unventilated fire took longer before the initial CO levels reached a lethal dose. Contrarily, the cabinet fires with different ventilation had similar initial heat release rate curves. Secondly, the cabinet fires kept producing CO after they first became vitiated and the fire died down before growing again to a second peak.

7.3 Impact of Ignition scenario and Type of Fire

The method of ignition and type of fire also had an impact on the onset of untenable conditions. Table 7-7 contains an overview of the time to untenable conditions for tests with smoldering and flaming sources and for sofa tests with and without ignitable liquids. There was negligible temperature rise and negligible reduction in oxygen in the smoldering tests (SM1 to SM4). In the smoldering cotton batting (SM1) and the smoldering sofa (SM4) tests, there was a notable increase in CO and smoke. However, in contrast to the smoldering fires, the flaming fires produced the most hazardous fire conditions; untenable thermal and toxic gas levels were reached much faster in the flaming fires compared to the smoldering fires. The same trend is also observed for smoke production. The flaming fires produced elevated temperatures with many of them exceeding the tenable threshold of 120°C. Oxygen concentrations at occupant level were reduced to about 10 to 16 percent along the path of egress and CO levels exceeded FED values of one, indicating lethal exposures. In addition, smoke density levels exceeded 2.1 OD/m, representing loss of visibility down below the 0.6 m (2 ft) height.

Table 7-7. Time (min) to Untenable Conditions for Tests Using Different Ignition Scenarios

Tenability Factor	Location	1.52 m (5 ft) Temperature ($\geq 120^o$ C)	Floor Heat Flux ($\geq 2.5 kw/m^2$)	1.52 m (5 ft) FED = 0.3	1.52 m (5 ft) FED = 1.0
Smoldering Bedding - no ventilation (SM1)	LR	N	N	95.80	115.52
	BR	N	N	85.07	109.00
Smoldering Sofa 1 - no ventilation (SM2)	LR	N	N	N	N
	BR	N	N	N	N
Smoldering Sofa 2 - no ventilation (SM3)	LR	N	N	N	N
	BR	N	N	N	N
Smoldering Sofa 3 - no ventilation (SM4)	LR	N	N	103.68	N
	BR	N	N	N	N
Sofa No ventilation (S1)	LR	13.95	N	19.40	27.62
	BR	N	N	21.33	30.28
Sofa Half Open Window (S3)	LR	13.18	14.52	15.02	16.87
	BR	14.80	N	15.60	17.43
Sofa Gas Half Open Window (S4)	LR	1.20	N	7.42	15.70
	BR	3.08	N	N/A	N/A

N – Not Reached

As noted in the experimental setup, achieving self-sustaining smolder can be difficult. This was evidenced in two of the sofa tests and in some pre-test trials of comforters. In test SM2 (as in SM3), the sofa did not develop a self-sustaining smoldering fire. Instead, the polyurethane foam in the sofa only pyrolized to a small diameter around the cartridge heater where the radiant heat was sufficient to affect it. Consequently, the conditions within the enclosure were quite benign as indicated in Tables 7-7. Though the environment was not hazardous in tests SM2 and SM3, there was visible smoke throughout the whole apartment and the sofas produced sufficient smoke to reach 0.4 OD/m at the 1.5 m (5 ft) elevation.

In SM1, cotton batting was used as a bounding source for bedding, since it has been established in prior works as a reliable medium for obtaining self-sustaining smolder with significant carbon monoxide production. In order to have a test that would last multiple hours, a large quantity of cotton batting (36 m^2 (384 ft^2)) was used and folded into a thick pile. It is expected that this source material and configuration may bound many actual products in ease of smolder, duration of smolder and CO production. This should be considered when applying the results to other smoldering applications. Table 7-7 shows that the cotton batting source was able to obtain untenable CO levels, but only after about 1.5 to 2 hours. At these times, approximately 16% to 34% of the batting had been consumed.

Within two hours, the self-sustaining smoldering sofa fire (SM4) was only able to produce enough CO to achieve the 0.3 FED criteria within the living room (the room of origin). For most people, the CO level was not untenable. At the end of the test, the CO levels were not returning to ambient conditions, but rather increasing near linearly. If the linear increase is extrapolated beyond the end of the test, an approximation of the time to untenable conditions can be estimated. Using the linear increase, it can be approximated that the other locations in the enclosure (excluding the LR 1.52 m location) would have reached the 0.3 FED threshold just over two hours. The 1.0 FED threshold can be approximated to have been reached after 140 minutes at the LR 1.52 m (5 ft) location, and at approximately 165 minutes for all other locations. This approximation is based off of the assumption that the sofa continued to produce CO at a linear rate. If the rate of CO production began to decrease, for example, if the amount of fuel became scarce, then this approximation would under predict the time to untenable conditions.

Figure 7-29 and Figure 7-30 show the temperature data for the class A and accelerated sofa fire tests, both with a half open window vent. The accelerated test reached the temperature threshold first, approximately twelve minutes before the non-accelerated fire in both rooms. The rapid ignition and growth of the accelerated fire account for the large difference in time, as the non-accelerated fire with the class A ignition scenario has to undergo a long growth period, thus taking much longer to reach the intensity needed to produce the untenable thermal conditions. However as seen in Table 7-3, the non-accelerated fire actually produced higher temperatures and sustained longer untenable conditions than the accelerated fire. This is due to the accelerated fire becoming vitiated and suppressed quickly after the gasoline burned whereas the non-accelerated sofa fire was able to involve more of the sofa (14% vs. 8%) and therefore provide more heat to the enclosure. Otherwise, the general growth of the fires was similar as shown in the temperature plots below. Mealy also showed that non-accelerated sofa fires with open door ventilation grew at the same rate as the accelerated sofa fire during the exponential growth rate period ((Mealy & Gottuk, Unventilated Compartment Fires, 2006)).

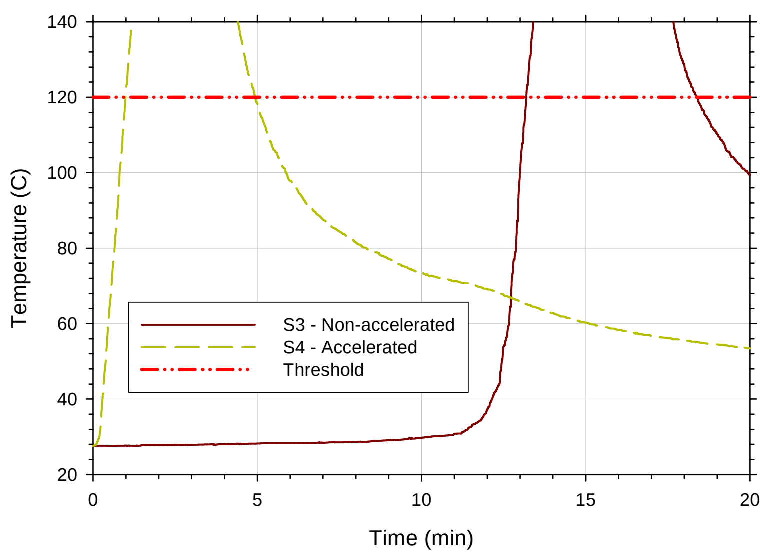


Figure 7-29. Temperature comparison for flaming class A ignition (S3) and accelerated (S4) sofa fires at 1.52 m (5 ft) in the living room

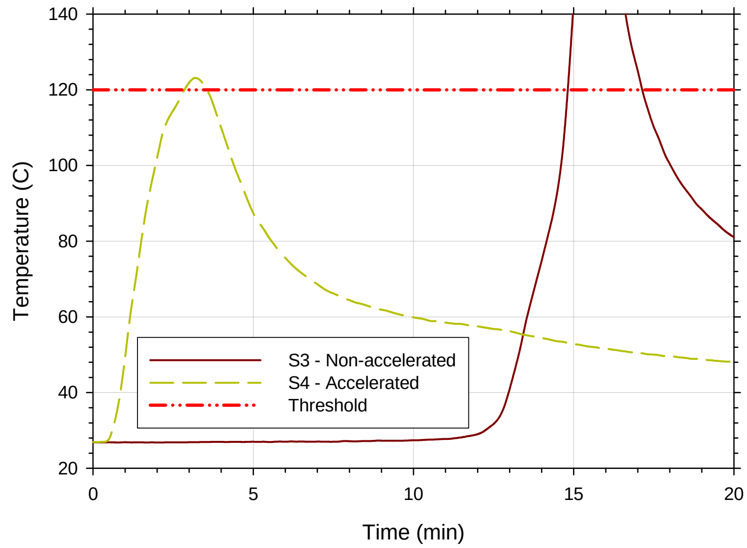


Figure 7-30. Temperature comparison for flaming class A ignition (S3) and accelerated (S4) sofa fires at 1.52 m (5 ft) in the bedroom

Figure 7-31 shows the heat flux data for the class A ignited and accelerated sofa tests. The accelerated test never reached the heat flux threshold, while the class A scenario reached it in 14.52 minutes. The accelerated fire did not burn for a very long time, thus it did not have a chance to grow to be large enough to produce the heat flux needed to reach the tenability threshold. The class A fire on the other hand, burned for a longer time (4.55 min), and therefore grew to a size where the threshold was reached.

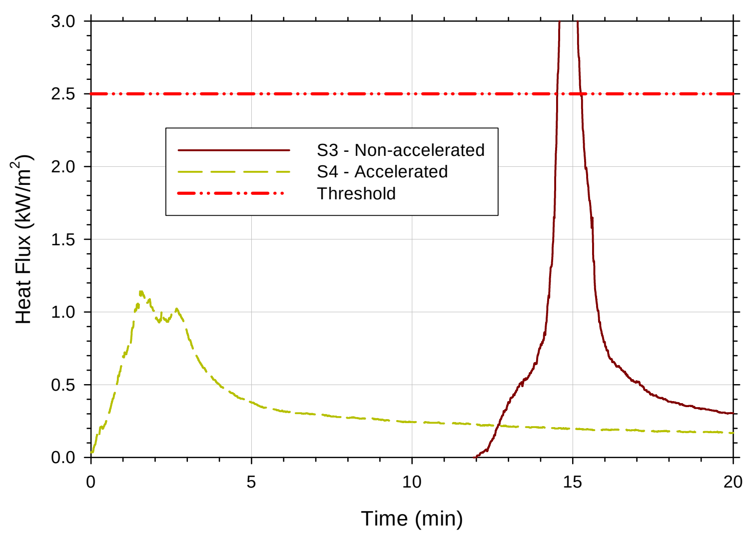


Figure 7-31. Heat flux comparison for class A and accelerated fires in the living room

Figure 7-32 and Figure 7-33 show the carbon monoxide FED for the class A ignited and accelerated sofa fires. In both rooms, the accelerated fire reached the 0.3 FED threshold eight to nine minutes before the class A fire. For the 1.0 FED threshold however, the accelerated fire only reached the threshold approximately one minute before the class A fire. The rapid growth and then lack of sustained burning of the accelerated fire quickly (within 3-4 min.) produced approximately 0.25% CO that then persisted over time within the closed space (see Figure 7-6). This exposure led to the relatively constant increase in FED for the accelerated test as shown in Figure 7-32 and Figure 7-33. For the class A ignition test (S3), CO production did not substantially start until approximately 12 min., but it then rose sharply to high concentrations (> 1.5%) in less than a minute (see Figure 7-3). Due to the rapid production of high levels of CO relative to when the fire starts to grow exponentially, the class A ignition may actually provide the greater threat to occupants in a small closed dwelling than an accelerated fire.

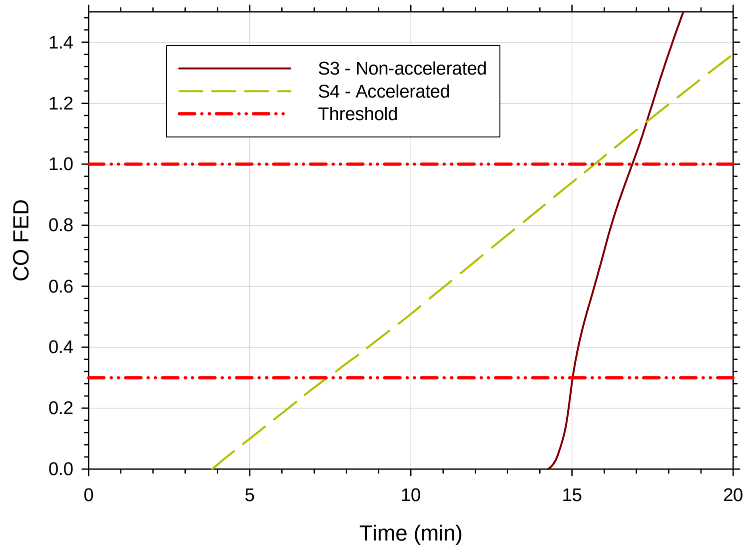


Figure 7-32. CO FED comparison of class A and accelerated fires at 1.52 m (5 ft) in the living room.

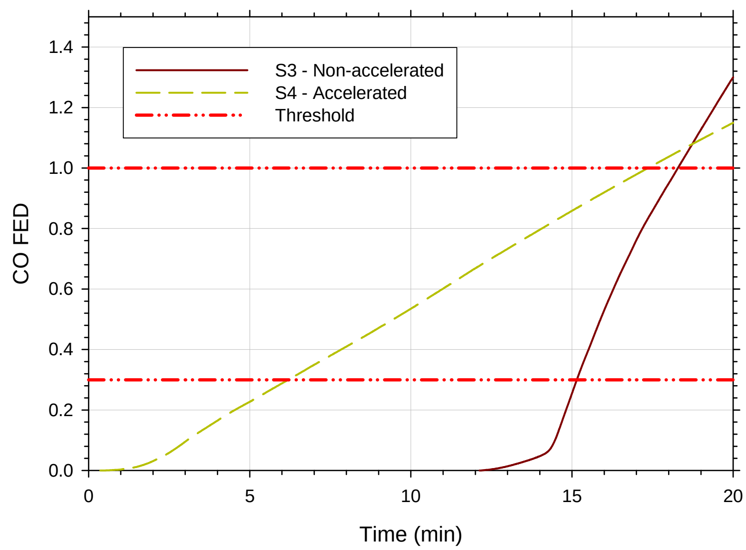


Figure 7-33. CO FED comparison of class A and accelerated fires at 1.52 m (5 ft) in the dining room.

From a thermal standpoint, the class A ignited sofa fire ultimately posed more of a hazard throughout the whole enclosure, reaching higher temperatures, heat fluxes and maintaining untenable conditions longer than the accelerated fire. Although, the rapid rise in temperature for the accelerated fire posed a untenable condition, it was only in the living room. Even in the living room, the accelerated fire never reached the tenability threshold for heat flux. For CO exposure, the accelerated fire reached the thresholds quicker, particularly for the 0.3 FED level. However the buildup of CO concentration was much less rapid and limited than in the non-accelerated fire, which could be a benefit to conscious people who notice smoke or people that have a detection system, and therefore have longer to escape prior to incapacitation from carbon monoxide.

By examination of the analysis presented above and Table 7-7, some general conclusions can be made about how the type of fire can affect tenability.

- Thermal
    - Smoldering fires had no thermal hazard.
    - Flaming fires produced elevated temperatures exceeding untenable levels in ~15 to 25 minutes from ignition. The exception was high cabinets with no ventilation or a half open window; these fires did not produce sustained untenable temperatures.
    - The limited ventilation, accelerated sofa fire reached untenable conditions faster than the class A ignition sofa fire; however, the class A flaming fire had higher temperatures and longer duration of untenable temperatures than the accelerated fire.
- CO
    - Smoldering fires take much longer to reach CO FED thresholds (~1.3 to 2 hours) than flaming fires (15 to 28 minutes from ignition of the class A source, i.e., the tissue boxes, and 8 to 21 minutes from ignition of the primary source, i.e., the sofa/cabinets).
    - The accelerated sofa fire reached the 0.3 FED in about half the time than the class A sofa fire (7 v 16 min.).

8 FIRE SCENE ANALYSIS

A fire scene analysis was conducted after each test. During each analysis, observations were made about fire patterns, fuel consumption, and soot deposition on the walls and carpet. This analysis was performed to determine the effects that different scenarios had on the condition of the enclosure and fuels, and to establish a basis for fire scene examination and analysis. Fire scene analysis was performed using the guidance of NFPA 921 "Guide for Fire and Explosion Investigation" (NFPA 921, 2008).

Previous work has been done to analyze forensic patterns and other aspects of post fire scene. In 1997, FEMA performed a study of forensic patterns in full-scale test fires in lab and real-world settings (FEMA, 1997). Their results provided confirmation of many forensic tools and beliefs, while disproving a few older elements of forensic analysis. All of these tests were performed in well ventilated structures and allowed to grow to flashover, however. Another study performed by Mealy and Gottuk (Mealy & Gottuk, 2006(a)) performed tests within underventilated enclosures. This study found that ventilation, in addition to ignition scenario, has an effect on the fire patterns and other forensic markers used in forensic analysis. The fires in this study, however, were ultimately ventilated and allowed to grow to flashover. This test was designed to fill in some of the blanks left over from previous testing. Tests were performed under various amounts of ventilation, without being ventilated, to determine the effects that ventilation may have on fire scene analysis.

In each test, new GWB targets and carpet samples were installed in the locations seen in Figure 4-14. In addition, the GWB around the fuel source was new for each test. For the sofa fires, the wall behind the sofa was replaced before each test, as well as one sheet of GWB on the corner wall to the right of the sofa. Also, the carpet under the sofa was replaced for each test. For cabinet fires, the false wall GWB was replaced for each test. In all tests, new GWB was placed on the ceiling directly over the fuel load.

8.1 Fire Patterns

The following photos illustrate the fire patterns resulting from sofa fire tests. The pattern shown in Figure 8-1 was observed after test S1, the no ventilation sofa test. A U-shaped pattern was observed on the wall behind the sofa, indicating that a fire plume was present. The amount of soot deposition remaining on the walls suggests that temperatures within the upper layer were not sufficient to oxidize the soot from the walls. Just above the center of the sofa, an area of clean burn (i.e., where temperatures were sufficient for soot oxidation, approximately 450-500° C (Stratakis & Stamatelos, 2003)) can be seen. The dark gray area of GWB directly above the center of the sofa is the area of clean burn.

Figure 8-2 displays the fire pattern above the sofa created in test S3, the half open window ventilation scenario. A U-shaped pattern was observed on the wall behind the sofa and smoke deposition can be seen on the side wall, beginning at the corner and rising diagonally away from the sofa. The wall behind the sofa was mostly free of soot, especially directly above the sofa, which indicates that the fire reached high enough temperatures to oxidize the soot deposited on the wall, resulting in the dark gray GWB, or clean burn, as opposed to the black soot covered areas.

Figure 8-3 and Figure 8-4display the fire pattern created in test S4, the accelerated half open window scenario. The pattern observed on the wall behind the sofa was not uniform to the same degree as the others. There was no clear U-shaped pattern as in the other sofa tests. Over the top of the left-hand side of the sofa, a clean burn area was observed, indicating an area of high heat. Over the right hand side of the sofa, there is noticeable soot deposition in a pattern that is somewhat a mirror image to the clean burn area. Especially in the upper right corner and along the top portions of the walls, there is black soot deposition, indicating that temperatures were not as high there as on the left hand side of the sofa.

Figure 8-5displays the fire pattern above the sofa created in test S2, the full open window ventilation test. Similar to test S1, there is the presence of a U-shaped pattern on the wall behind the sofa. However, in test S2 with the larger vent, the pattern is not marked by heavy black soot, but rather by discoloration of the gypsum wall board where the soot had been burned off (i.e., a clean burn). The clean burn can be seen in the photo on the wall behind the sofa as well as on the ceiling and on the upper portion of the wall to the right. The extended clean burn area demonstrates that the fire in this test was larger than that observed in test S1, consistent with the measured heat release rates.

Figure 8-1. Fire pattern from test S1 (no ventilation)

Figure 8-2. Fire pattern from test S3 (half open window)

Figure 8-3. Fire pattern from test S4 (half open window accelerated)

Figure 8-4 Fire Pattern from test S4 (half open window accelerated)

Figure 8-5. Fire pattern from test S2 (full open window)

The following photos display the carpet burn patterns for the sofa fires. Figure 8-6 shows that carpet burn pattern that was common to all class A ignited sofa tests (S1, S2, S3). This pattern was a semi-circular shaped burn pattern found beneath the sofa after each test. This particular burn pattern resulted from hot, liquefied polyurethane that dripped from the sofa, and then burned outward in the semi-circular pattern observed. Also noticeable in the photo are springs from the sofa that fell to the floor as the sofa burned. Figure 8-7 shows the carpet burn pattern resulting from the accelerated sofa test (S4). The triangular burn pattern in the front of the carpet section where the gasoline trailer started is very different from the pattern under the sofa where the polyurethane foam pooled and burned. The triangular pattern has much more of the carpet burned away, exposing the GWB underneath, consistent with higher heat input from a longer burning fire located here than the pattern located under the sofa. The liquefied polyurethane fire pattern is smaller in the accelerate sofa test, due to the relatively brief period of burning during this test compared to the class A ignited sofa fire.

Figure 8-6. Burn pattern under sofa common to all accidental tests.

Figure 8-7. Burn pattern under and in front of sofa during accelerated test

The following figures demonstrate the fire patterns observed following the low cabinet fire tests. Figure 8-8 shows the pattern observed following the unventilated scenario and Figure 8-9 shows the pattern observed after the half open window ventilation scenario. Similar U-shaped burn patterns were observed after each of these tests. Furthermore, similar amounts of soot deposition were present on the wall that the cabinets were mounted on. By visual inspection, it is difficult to discern much difference in patterns that could be associated with the different ventilation scenarios. The false wall and ceiling were mostly destroyed in test CL3 (see Figure 8-10), and therefore no fire pattern analysis could be made for this case.

Figure 8-8. Fire pattern from test CL1 (no ventilation)

Figure 8-9. Fire pattern from test CL2 (half open window)

Figure 8-10. Fire pattern from test CL3 (open door)

Figure 8-11 through Figure 8-14illustrate the fire patterns observed following the high cabinet fire tests. Figure 8-11 shows the fire pattern resulting from test CH1, an unventilated scenario. In this test, the first cabinet is completely consumed, along with most of the second cabinet and some of the third cabinet. There is a diagonal burn pattern originating from the bottom left toward the top right of the cabinet array. In addition, there is a clean burn above the right side of the second cabinet, indicating this was the area exposed to the highest temperatures. Patterns such as these can indicate where a fire started and how it progressed; in this case, at the leftmost cabinet, then moving right. It is also interesting to note that the clean burn is not located at or above the point of origin, but rather further down the cabinet array.

Figure 8-12 shows the fire pattern resulting from test CH2, the half open window ventilation scenario. The first two cabinets were completely consumed in this test, as well as most of the third cabinet. The remainder of the third and fourth cabinets fell off of the wall and were located on the floor beneath the cabinet array. Again, a diagonal burn pattern extends from the bottom left toward the top right. These observations again can be used to determine where a fire originated. Similar to test CH1, the greatest damage to the ceiling, characterized by the clean burn area, is above the second cabinet, not above the point of origin.

Figure 8-13 shows the fire pattern left by test CH3, the open door ventilation test. The lack of soot deposition and many clean burn areas indicate that this fire reached higher temperatures than the previous fires, which is in agreement with the ventilation scenarios (maximum room of origin temperature of 425°C in CH1, 534°C in CH2, and 710°C in CH3). The burn pattern originating from the floor is a result of the cabinets falling off of the wall and continuing to burn on the floor. In test CH3, it is difficult to determine where the fire started based on fire patterns due to the cabinet array falling off the wall early in the test. In test CH4, the false wall and ceiling were completely destroyed, thus fire patterns are of limited value (see Figure 8-14). Given the small protected areas of studs on the right side of the array, the general progression of the fire moving left to right can be inferred.

Figure 8-11. Fire pattern from test CH1 (no ventilation)

Figure 8-12. Fire pattern from test CH2 (half open window)

Figure 8-13. Fire pattern from test CH3 (no window)

Figure 8-14. Fire pattern of test CH4 (open door)

8.2 Fuel Source Consumption

The following figures display the amount of fuel consumed during the sofa fire tests. Table 8-1 shows the percentage of mass lost for each test. Tests S2 and CH3 were both suppressed during the growth stage, which had an impact on how much fuel was allowed to be consumed. Tests CL3 and CH4 were also manually suppressed, however, the fires were mostly done burning at the time of suppression, and therefore the mass consumption was not significantly affected. Test CH4 mass data is only available until the cabinets fell off of the wall. This is due to falling debris landing partially on and off of the mass loss platform, thus disrupting the measurement. Figure 8-15 shows the sofa after the unventilated test (S1). A large portion of the seat was consumed, in addition to some of the seat back. The wood frame, while somewhat charred on the back frame of the sofa, was still mostly intact. Figure 8-16 displays the sofa condition after the half open window ventilation test (S3). Again, much of the sofa seat was consumed and slightly more of the seat back was consumed than in the no ventilation test. Figure 8-17 shows the sofa condition after the full open window ventilation test (S2). Most of the polyurethane from the seat and seat back was consumed. The back portion of the sofa was also consumed and a large portion of the wood frame in the seat back was heavily charred. As in previous observations, a trend emerges across ventilation differences. The less ventilated a fire is, less of the fuel load is consumed, due to the fire becoming vitiated earlier.

A similar trend was observed for the cabinet fires. The unventilated tests consumed the first two cabinets and the half open window tests consumed the same amount or a little more. The open door test consumed almost the entire fuel load. The greater the ventilation opening, the larger amount of fuel consumed.

Figure 8-17 shows the condition of the sofa after the accelerated half open window test (S4). A large portion of the seat and seat back foam was consumed. There was little charring of the wood frame. When compared to the equally ventilated class A ignited sofa fire (S3), seen in Figure 8-16, there are no obvious visual indications as to differentiate how the fires were initiated. The charring on the front of the sofa could indicate the presence of a trailer; however, similar patterns could also result from household combustibles located at the foot of the sofa. A test for ignitable liquids was performed on the sofa by the ATF Laboratory to determine if ignitable liquids were used. Samples were taken from the area directly around the burned area as well as the armrests. None of the samples tested positive for ignitable liquids.

Table 8-1. Mass Loss

Test	Ventilation	Mass Loss (kg)
SM1	No Ventilation	4.20
SM2	No Ventilation	N/M
SM3	No Ventilation	N/M
SM4	No Ventilation	1.09
S1	No Ventilation	5.80
S3	Half Open Window	5.08
S4	Half Open Window Accelerate	6.75
S2	Full Open Window	3.99*
CL1	No Ventilation	30.42
CL2	Half Open Window	30.95
CL3	Open Door	49.87*
CH1	No Ventilation	28.77
CH2	Half Open Window	40.94
CH3	No BR Window	29.75**
CH4	Open Door	48.45***

* - Manual suppression used (at 15.9 min in S2 and at 33.8 min. in CL3. Test CL3 was mostly finished burning at time of suppression.

** - Cabinets fell off of the false wall in test CH3 at 29.6 minutes. Analysis was discontinued at this time.

*** - Mass loss data only available for test CH4 until cabinets fell off of wall at 31.0 min. Manual Suppression followed at 36.6 min.

N/M – Mass loss not measurable

Figure 8-15. Sofa after test S1 (no ventilation)

Figure 8-16. Sofa after test S3 (half open window)

Figure 8-17. Sofa after test S2 (full open window)

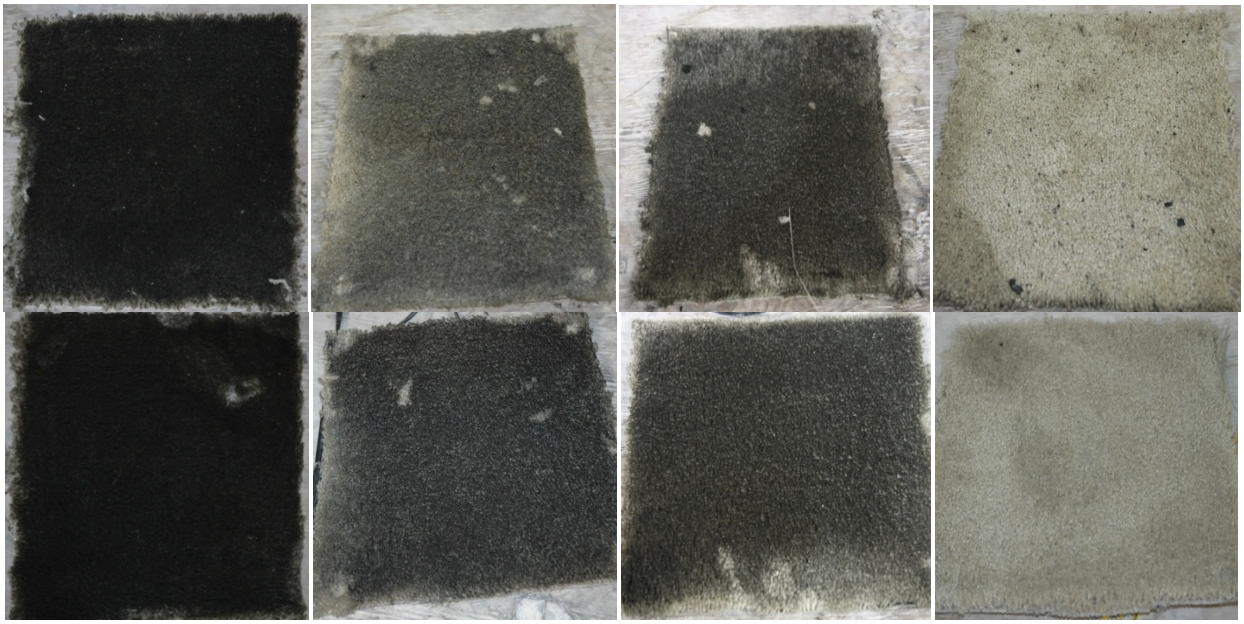
Figure 8-18. Sofa after test S4 (half open window accelerated)

8.3 Soot Deposition

A comparison of the soot deposition on carpet samples present in the enclosure during each of the sofa fire tests is presented in Figure 8-19. The sample from test S1 (no ventilation) (Figure 8-19a) has a high level of soot deposition and is very dark in color. The level of deposition on the carpet sample from S3 (half open window) (Figure 8-19b) is lighter than the S1 sample even though there was more mass burned in S3 (5.7 kg) than in S1 (3.4 kg). In addition, sofa S3 reached a higher heat release rate (862 kW) than the S1 sofa with no ventilation (353 kW). The sample from the full open window fire S2 (Figure 8-19d) has very little visible deposition on it, and the sofa had 4.8 kg of mass loss (less than S3 with the half open test). However, test S2 was manually suppressed as it approached a peak heat release rate of 1032 kW. These results demonstrate that the level of soot deposition on flooring has is dependent upon ventilation and not on the direct amount of fuel burned. This is also evident in that the smoldering batting fire consumed 4.2 kg of fuel (i.e., more than two of the sofa fires) with no visible deposition. There was no visible deposition during any of the smoldering tests; therefore, no individual photos of targets or carpet are presented.

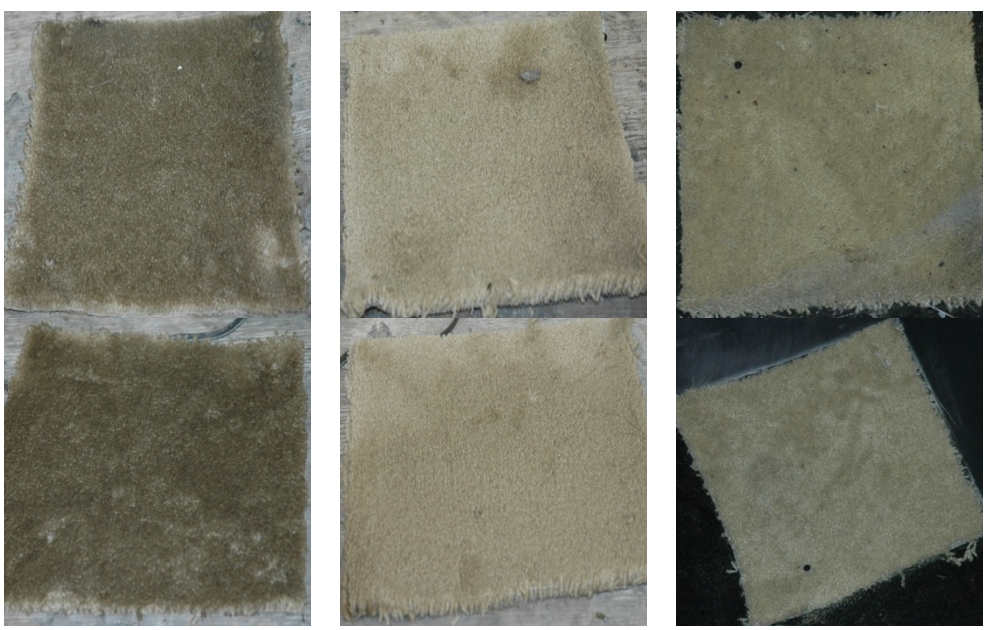
However for the sofa fires, with more ventilation, there was less visible soot deposition on the carpet. A similar trend was also observed in the cabinet tests (see Figure 8-20 and Figure 8-21). (Note: Samples from CL3 and CL4 were photographed in a darker location of the lab due lab usage restrictions; therefore the lighting of the photos may impact the relative comparison to other samples.) This result is consistent with the lower ventilated fires burning less efficiently and producing higher smoke yields (Gottuk & Lattimer, 2008). Unfortunately, due to the optical density meters (ODMs) becoming saturated at the peak levels of smoke in the flaming fires, a comparison of the maximum smoke yields cannot be made. Figure 1-22 shows the calculated smoke concentration in the living room using the ODM measurements at the 2.41 m level and a specific extinction coefficient of 8.7 (Mulholland & Croarkin, 2000). The curves show the limit of the ODM measurements in the max concentration being capped slightly over 0.55 kg/m^3. The concentration curves indicate that the unventilated sofa fire (S1) had a higher overall smoke concentration early in the fire compared to the sofa fire with the half open window (S3). This is consistent with the less ventilated fire having a higher smoke yield. Later, after the fires had extinguished, the smoke concentration curves reverse and the S3 levels are higher than the S1 levels. This in part may also reflect a greater amount of soot deposition from soot dropping out of the gas layer with the cooler, unventilated fire.

A source of uncertainty in this analysis is the full contribution of the time effect that could have influenced the deposition. Test S1 had the longest duration by far of any sofa test, and S2 had the shortest duration. The length of exposure to the environment inside the enclosure could have had some effect on the amount of soot deposited. This hypothesis assumes that soot settling would be a primary mechanism that continues over the duration of the test and possibly until the photographs were taken. The continuously declining concentrations in Figure 1-22 are consistent with this hypothesis. Additional data presented below also demonstrates that soot settling out of the gas is the primary deposition mechanism on horizontal surfaces. In some areas farther away from the fire, where the layer descends to the floor, it is unclear how much of the deposition on the carpet may be due to thermophoretic forces (driven by gas to carpet temperature gradients). Riahi and Beyler are investigating the mechanisms of smoke deposition in fires in an ongoing NIJ grant (Riahi & Beyler, 2009).



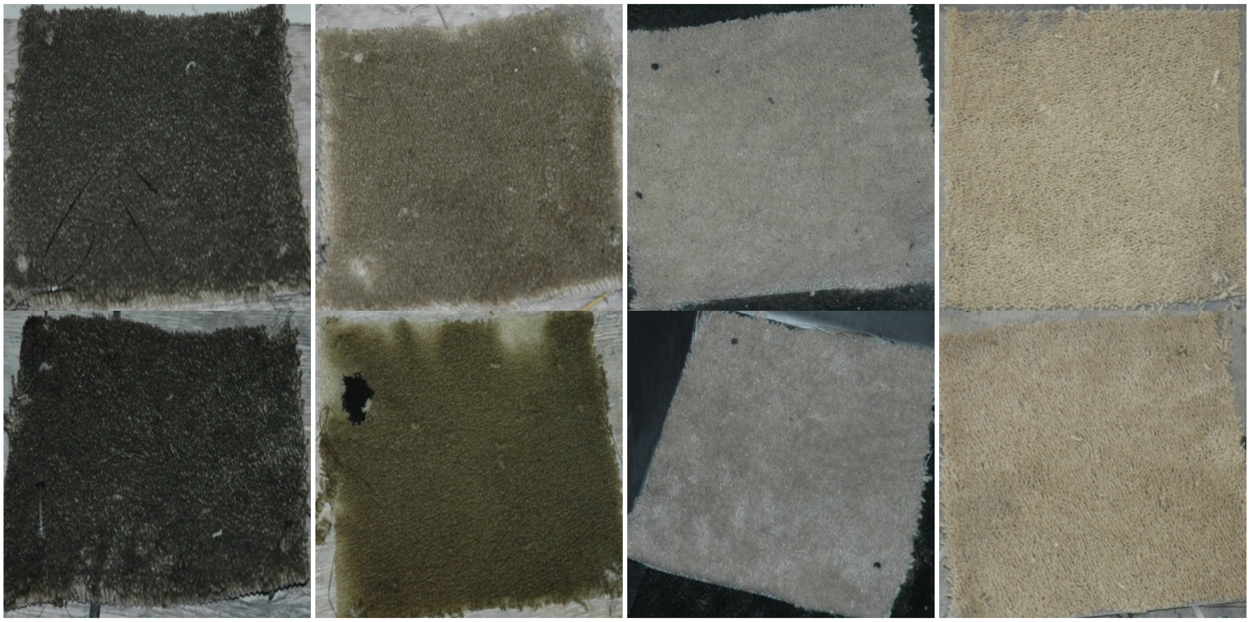
(a) S1 – no ventilation (b) S3-half open window (c) S4 half open window accelerated (d) S2 – full open window

Figure 8-19. Soot deposition on carpet samples from the living room (top) and bedroom (bottom) for sofa tests



(a) CL1 – no ventilation (b) CL2 – half open window (c) CL3 – open door

Figure 8-20. Soot deposition on carpet samples from the living room (top) and bedroom (bottom) for low cabinet tests



a) CH1 – no ventilation b) CH2 – half open window c) CH3 – no BR window d) CH4 – open door

Figure 8-21. Soot deposition on carpet samples from the living room (top) and bedroom (bottom) for high cabinet tests

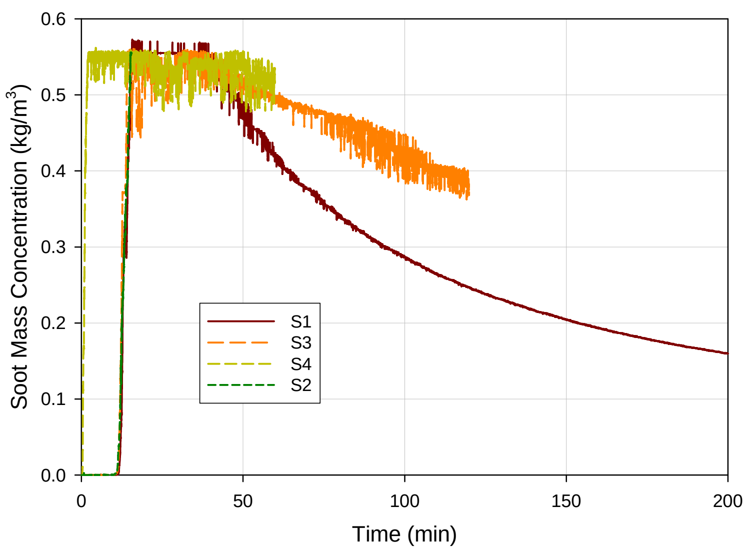


Figure 8-22. Soot mass concentration in the living room for sofa tests

In each test, painted 2.44 m (8 ft) by 0.61 m (2 ft) GWB targets were installed in each room of the test enclosure to allow for soot deposition. A collage of the targets from the sofa fire tests is provided in Figure 8-23 through Figure 8-26. The collages are similar in that the rooms that are the most remote (bedroom and kitchen) from the fire room do not have a discernable layer; rather, they have fairly uniform deposition from floor to ceiling. Conversely, the rooms closest to the fire (living room and dining room) had noticeable lines of demarcation of the layer, with the top portion of the target having soot deposition, and the bottom being relatively clean. A similar trend was seen in the cabinet tests as well, with the rooms remote from the fire exhibiting uniform deposition (living room and bedroom) while the rooms in close proximity to the fire (kitchen and dining room) had distinct deposition heights. This finding is useful in the determination of the room of origin. The farther away from a fire, the more even the deposition is expected to be, while rooms close to the fire will have more distinct deposition heights. These trends were also observed in the cabinet tests, as seen in Figure 8-29 to Figure 8-34, with the kitchen and the dining room having a distinct layer and the living room and bedroom having even soot deposition.

Differences in soot deposition from the living room to the bedroom are impacted by differences in thermophoretic forces (driven by gas to wall temperature gradients) and by overall soot losses as the fire gases move from the fire room to the bedroom. The effects of soot losses and dilution of the smoke as it moves to the bedroom is reflected in the lower smoke levels measured in the bedroom compared to the living room. Once the smoke is in the bedroom, lower temperature gradients between the gas and wall surface can impact the thermophoretic deposition compared to the living room. In all tests, the fire room target had the darkest deposition (based on the photos, Test S3 appears to be a slight exception to this). In the rooms closest to the fire room (the living room and dining room in the case of the sofa fires), the upper layer was hot, and created strong thermophoretic forces for soot deposition to the walls in the layer. This layer deposition can be seen in Figure 8-23 - Figure 8-26, with the soot deposited high on the target and the bottom of the target relatively clean. In the rooms farther removed from the fire (the kitchen and bedroom in the case of the sofa fires), the upper layer begins to cool and mix with the lower layer. This results in the soot being evenly deposited over the entire height of the target. In addition, in some tests (S3, CL1, CH1, and CH2 in particular) the carpet samples are noticeably darker in the bedroom as opposd to the living room.

As an example of this, Figure 8-27 shows the living room temperature profile for test S1, the no ventilation sofa test. In the living room, the 1.22 m location (peaking at ~160°C) is the level of transition between the hot upper layer and the cool lower layer. Above this elevation, the temperatures are high and closely grouped. Below this level the temperatures are also grouped together, but at lower temperatures (> 100°C). Figure 8-28 shows the temperature profile in the bedroom for the same test. In this test, all of the temperatures are lower than in the living room, and are much closer together, with a smaller gradient floor to ceiling compared to the living room. There is not a clearly visible layer interface in the bedroom as the gases are fairly well mixed. Consequently, the soot deposited on the wall more evenly from floor to ceiling. In addition, the temperatures were generally under 100°C (with some peaks less than 150°C). These temperatures are lower than the living room upper layer temperature and are more comparable to the lower layer temperatures in the living room. These lower temperatures in the bedroom correspond to lower thermophoretic velocities (i.e., deposition forces) than in the upper layer of the living room. This is consistent with the heavier deposition seen in the living room. Riahi and Beyler have developed a model for the thermophoretic velocity and are including samples from these tests in their work (2009).

A comparison of the soot deposition on the living room wall board sample in Figure 8-23 to the floor carpet sample in Figure 8-19a shows that the carpet deposition is much greater than the wall. Particularly in the lower layer in the living room, the wall had very little smoke deposition. This indicates that soot drooping out of the gas layer is the primary mechanism for deposition on horizontal surfaces.

Figure 8-23. Test S1 (no ventilation) GWB targets (BR, K, DR, LR)

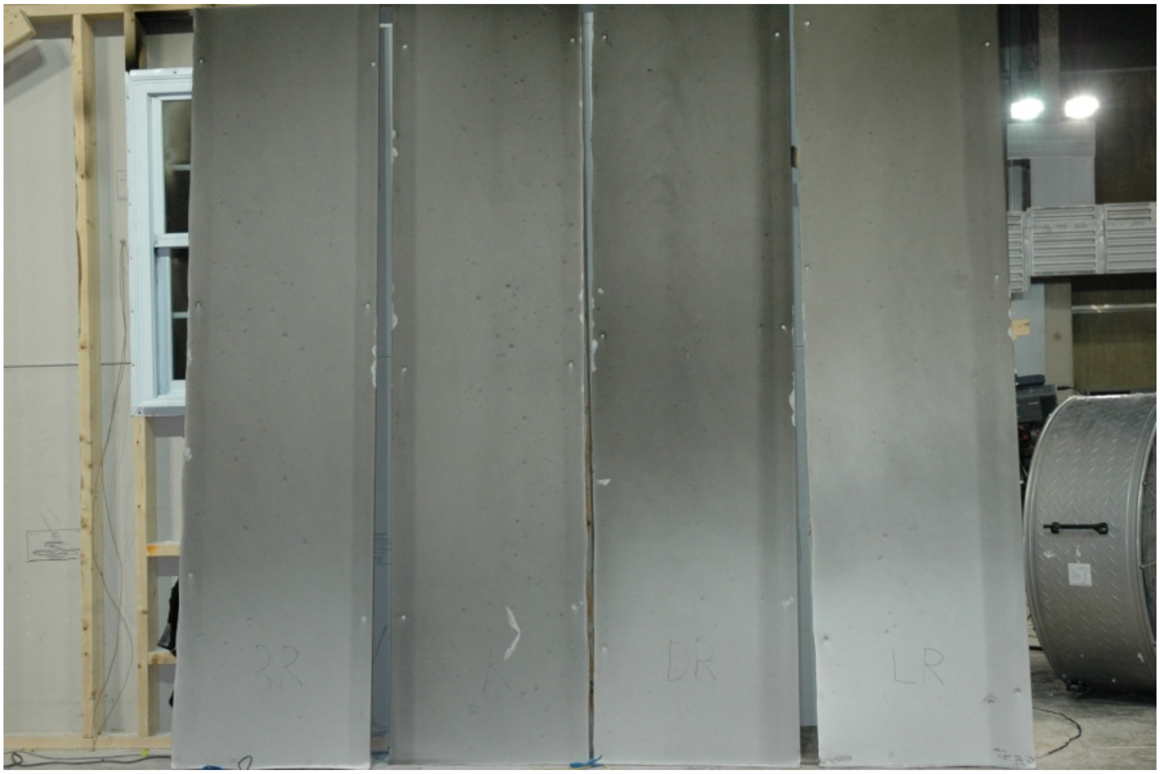


Figure 8-24. Test S3 (half open window) GWB targets (BR, K, DR, LR)

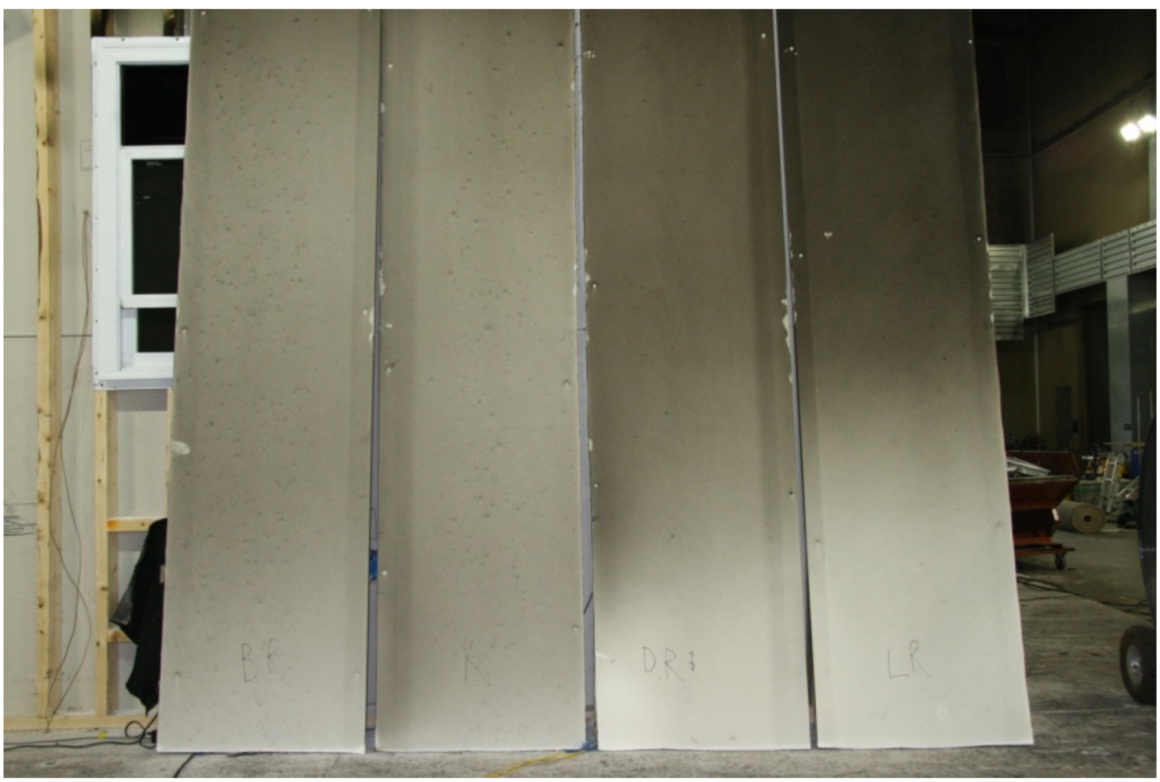


Figure 8-25. Test S4 (half open window accelerated) GWB targets (BR, K, DR, LR)

Figure 8-26. Test S2 (full open window) GWB targets (K, BR, DR, LR)

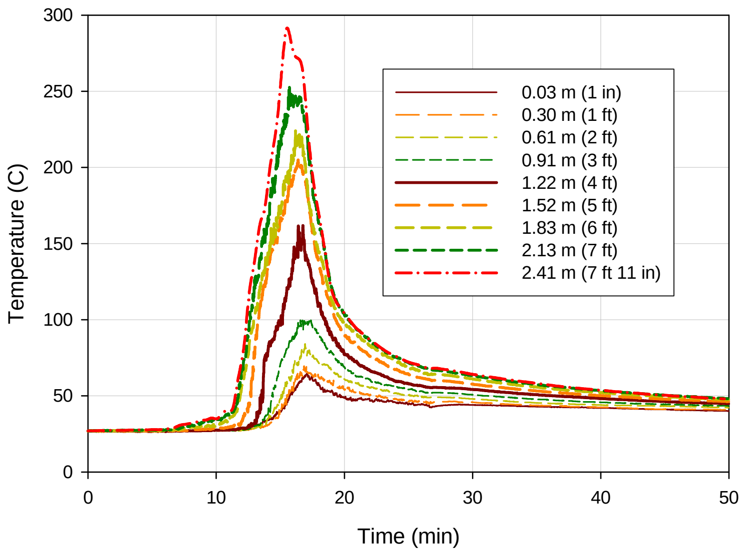


Figure 8-27. Living room temperature profiles for sofa test S1 (no ventilation)

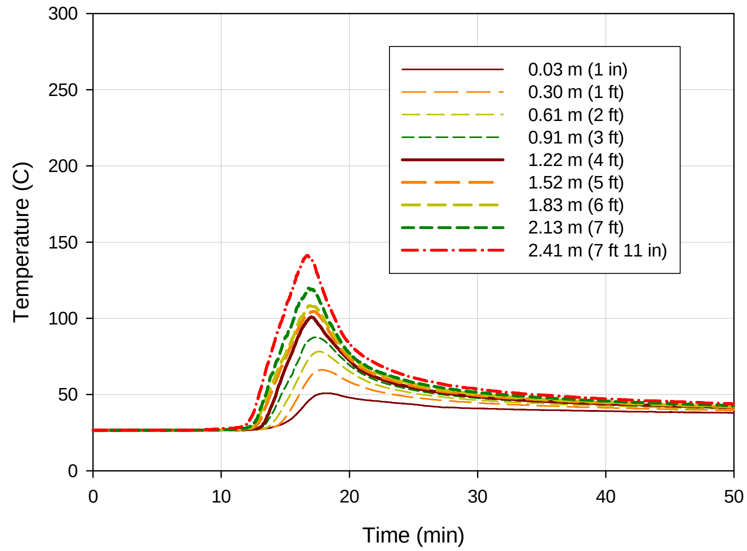


Figure 8-28. Bedroom temperature profile for sofa test S1 (no ventilation)

Figure 8-29. Test CL1 (no ventilation) GWB targets (BR, DR, K, LR)

Figure 8-30. Test CL2 (half open window) GWB targets (BR, DR, K, LR)

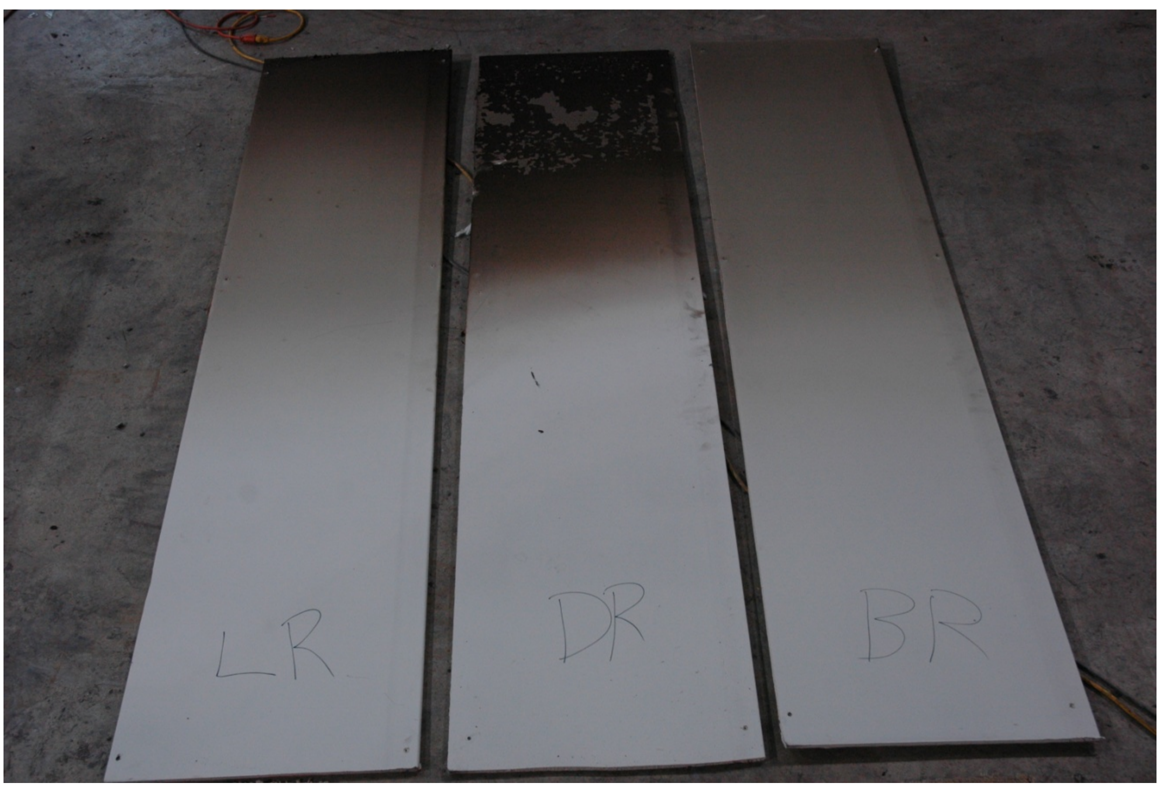


Figure 8-31. Test CL3 (open door) GWB targets (LR, DR, BR) (K target was destroyed during test)

Figure 8-32. Test CH1 (no ventilation) GWB targets (BR, K, DR, LR)

Figure 8-33. Test CH2 (half open window) GWB targets (BR, DR, K, LR)

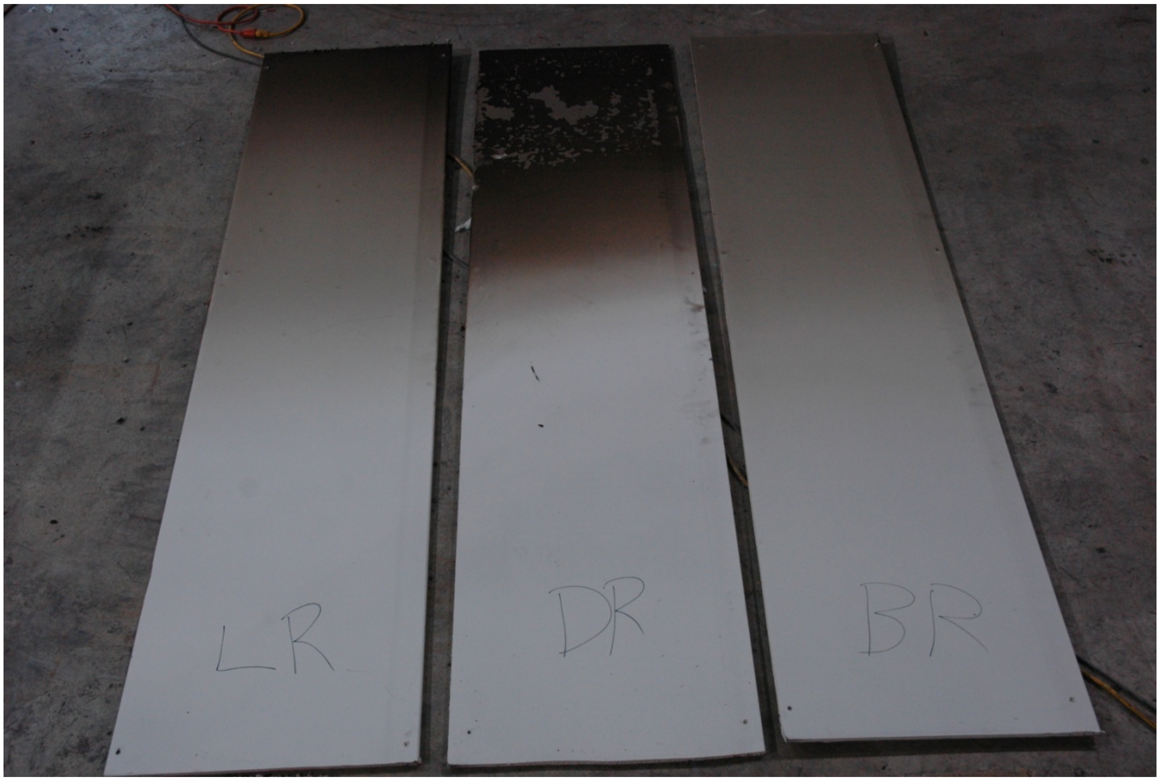


Figure 8-34. Test CH4 (open door) GWB targets (LR, DR, BR)
(K target was destroyed during test)

8.4 Comparison of Smoldering and Flaming Fires

The condition of the room and fuel source were very different when comparing smoldering and flaming tests. Figure 8-35 shows a photograph of the living room walls and sofa prior to test S1, the accidental no ventilation sofa test. The demarcation on the wall behind the sofa and the ceiling were caused by removal of GWB that had been put in place during the burner tests, and then removed prior to test S1. Figure 8-36 shows the room and sofa after the fire test was performed. A large portion of the sofa seat was consumed, and the rest of the seat was charred. The walls were coated with dark black soot, as well as the carpet and other room contents.

Figure 8-37 shows the sofa and living room walls prior to test SM2, a no ventilation smoldering sofa test. As mentioned previously, the demarcation on the walls was caused by the previous burner tests conducted in the enclosure. Figure 8-38 shows the living room and sofa after the test was conducted. The walls have little to no deposition, and only a small portion of the sofa seat has been charred or consumed. Figure 8-39 shows the sofa after test SM4, the smoldering sofa test performed with a different type of sofa. There is much less damage present than seen in the flaming test, and the rest of the sofa is not charred or heavily coated with soot. Figure 8-40 shows the GWB in the dining room after test SM4. There is again a lack of smoke deposition, as seen in the previous smoldering test. The lack of noticeable deposition in smoldering tests is consistent with the smoke being lighter colored (more grayish) and not attaining the high concentrations as the smoke produced in the flaming fires.

Figure 8-35. Before flaming sofa test (S1 – no ventilation)

Figure 8-36. After flaming sofa test (S1 – no ventilation)

Figure 8-37. Before smoldering sofa test (SM2 – no ventilation)

Figure 8-38. After smoldering sofa test (SM2 – no ventilation) (Note: this photo actually portrays the scene darker than observed on site due to the lighting in the space when the photo was taken.)

Figure 8-39. Damage to sofa after smoldering test (SM4 – no ventilation)

Figure 8-40. Soot deposition on GWB target after smoldering sofa test (SM4 – no ventilation)

9 CONCLUSIONS

A series of fifteen full-scale fires was conducted within a four room, apartment-style enclosure 41.8 m^2 (450 ft^2), with the intent of characterizing the effects of limited ventilation on fires. The tests included four different fuel source configurations: folded cotton batting, sofas, and wooden cabinets located both high and low in the enclosure. Fires were initiated via cartridge heaters (smoldering fires), flaming Class A combustibles (non-accelerated flaming fires), and gasoline (accelerated flaming fire). Ventilation conditions ranged from a completely closed enclosure to various window vents to an open door. The goals of this research were to 1) examine the effects of ventilation on general fire dynamics, including fire growth, smoke and gas production, and vitiation; 2) determine the effect of ventilation on tenability factors including temperature, heat flux and carbon monoxide; and 3) to determine the effect of ventilation and ignition scenario on the ability to utilize forensic tools to determine the cause and progression of a fire.

Fires without enough ventilation became vitiated and ceased to grow (and sometimes extinguished), while fires with enough ventilation continued to grow. A critical ventilation size that allows the continued growth of a fire was determined. Based on these tests and previous work, the critical size for the sofa fires is close to or just larger than a full open window (0.24 m^2). All sofa tests with less ventilation became vitiated and self-extinguished. For the low cabinets, the critical ventilation size can be bracketed between the half open window ventilation (0.12 m^2) and the open door ventilation (1.85 m^2). For the high cabinets, it can be bracketed between the half open window and the window removed (0.67 m^2) . Below this critical ventilation size, the cabinet fires continued to vitiate (i.e., reduce oxygen concentration) and became suppressed. However contrary to the sofa fires, the cabinet fires rekindled and grew after being suppressed once the oxygen level at the base of the fire reached a critical value. Some of the cabinet fires had several peaks in fire growth over several hours. Each peak was accompanied by a sharp rise in temperature and carbon monoxide concentrations.

The suppression of fires was caused due to the reduction of oxygen and the increase in diluents, particularly carbon dioxide. Below a given oxygen concentration, a fire will not be able to burn. This concentration is characterized as the lower oxygen index (LOI). The LOI was determined experimentally for each test that vitiated and self suppressed. This was achieved by examining oxygen concentration at the base of the fire at times when the upper layer oxygen and temperature sharply changed, indicative of a change in the burning of the fuel. For example, when the temperature at the ceiling suddenly dropped, this signified that the fire was being suppressed and going out. It was found that the sofa had an approximate LOI of 18-19% oxygen and the cabinets had an LOI of approximately 16% oxygen. This experimental data was then compared to values calculated using Beyler's Unified Model of Fire Suppression (Beyler, 1992), based on the fire point theory. The values calculated from the fire suppression model were in general agreement with the experimental values. This validation of the of the fire point theory method demonstrates that the LOI data from this study and the unifired model of fire suppression can be used in analyzing other real world fires that occur in different size structures and with different fires. This modeling tool can aid investigators in determining when or if a fire became underventilated.

Although ventilation ultimately influenced how large a fire could grow (i.e. peak heat release rate and temperature, whether a fire would vitiate and self suppress), the ventilation opening did not have an effect on the initial fire growth rate. For approximately the first 5-10 minutes after the ignition of the main fuel item, the heat release rate for each test was very similar to others of the same fuel type and orientation, regardless of the vent opening. This indicates that the initial fire growth rate for an open enclosure that is greater than 41.8 m^2 (450 ft^2) is not significantly affected by ventilation openings. As an enclosure becomes smaller, ventilation area will become more of a limiting factor.

Ventilation had a noticeable effect on tenability. In general, the fires became more hazardous with ventilation than without, sustaining untenable temperatures longer and reaching untenable CO exposures sooner. For no ventilation, sofa and low cabinet fires, thermal hazards generally preceded CO hazards in the areas proximate to the fire, while in remote areas the temperatures remained tenable and hazardous levels of CO developed. With ventilation, these fires produced CO and thermal hazards at approximately the same time, with conditions lasting longer than with no ventilation. For high cabinet fires, thermally untenable conditions were not reached throughout the compartment for no ventilation and half open window ventilation tests; however untenable CO levels were present. For greater ventilation sizes, the high cabinets created thermal and CO hazards at approximately the same time, similar to the sofa and low cabinet fires.

In terms of fuel source, sofa fires posed a faster thermal hazard than the cabinet fires, resulting in shorter times to untenable temperatures (~14-15 min. v. ~18-27 min.) and higher peak temperatures. There was no consistent trend of whether sofa or cabinet fires developed untenable CO hazards quicker; it depended on ventilation and location of the cabinets (high or low in the space). All the fires produced lethal CO levels in about 15 to 30 minutes.

The ignition scenario also had an effect on the time to untenable conditions within the enclosure. Smoldering fires posed no thermal hazard, and took much longer to reach untenable CO levels as opposed to the two flaming scenarios (generally on the order of hours as opposed to 15-30 minutes for non-accelerated flaming fires). Accelerated flaming ignition reached tenability criteria much faster than the non-accelerated scenario (1-3 min v 13-15 min); however, the class A non-accelerated flaming fire had higher temperatures and longer durations of untenable temperatures than the accelerated fire.

Soot deposition can play a key role in forensic analysis of compartment fires. As is typical with sufficient ventilation, the wall and ceiling areas around the fuel source were characterized by clean burns, where the soot was burned off of the surface. The size of the clean burn area is proportional to the size of the fire, which depends on the ventilation. Generally for these tests, the less ventilation a test had, the more soot was deposited on the carpet within the enclosure. Also, soot deposition can be used to aid in the area of origin determination. It was observed that the walls in the fire room had clear demarcation and very dark soot deposits in the upper portion of the room. Further from the fire room, the demarcation lines were not as clear and the soot deposits were much lighter and more uniform floor to ceiling.

Smoldering fires produced little to no visible soot deposition throughout the enclosure, while flaming fires generally coated all surfaces with varying levels of soot. Therefore, distinguishing between a smoldering fire and a flaming fire proved to be relatively easy. Distinguishing between an accelerated and non-accelerated fire in under-ventilated conditions proved to be more difficult. Both the accelerated and non-accelerated fires produced similar fire patterns and soot deposition on the walls. Approximately the same amount of fuel was consumed during each test, leaving the same general fire pattern on the sofas. The only obviously distinguishing feature that differentiated the accelerated and the non-accelerated fire was the trailer pattern that was left on the floor. Chemical testing for ignitable liquid residue was ineffective at determining the presence of ignitable liquids on various sofa samples.

In summary, this research provides new insight into the effects of ventilation on various fire dynamics, tenability, and forensic analysis of limited ventilation enclosure fires. Further research in this area would enhance the knowledge of these effects. Due to the limited amount of tests in this research, no tests were performed multiple times. Doing so would further validate the findings of this research and the applicability of the findings. In addition, the limited amount of ventilation sizes used limited the effectiveness of fully determining the critical ventilation size needed to sustain the growth of a fire. Finally, research on larger enclosures and multiple story structures would further enhance the knowledge of fire development, tenability effects and the applicability of the unified suppression model to extrapolate data to other fire scenarios with limited ventilation. In particular, a two story structure may allow longer fire development and increased thermal and toxic gas exposures to upper floor occupants even for unventilated enclosures of the same floor area as a single story structure. This would be due to the filling effect of upper levels while allowing the fire to remain in the lower layer. However, local ventilation restrictions, such as interior doors to the fire room, may still act to vitiate the environment near the base of the fire and partially suppress the fire. More work is needed to develop a full understanding of these different effects and the validation and use of the unified suppression model for larger and multiple story structures.

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APPENDIX A

CONSTRUCTION DRAWINGS

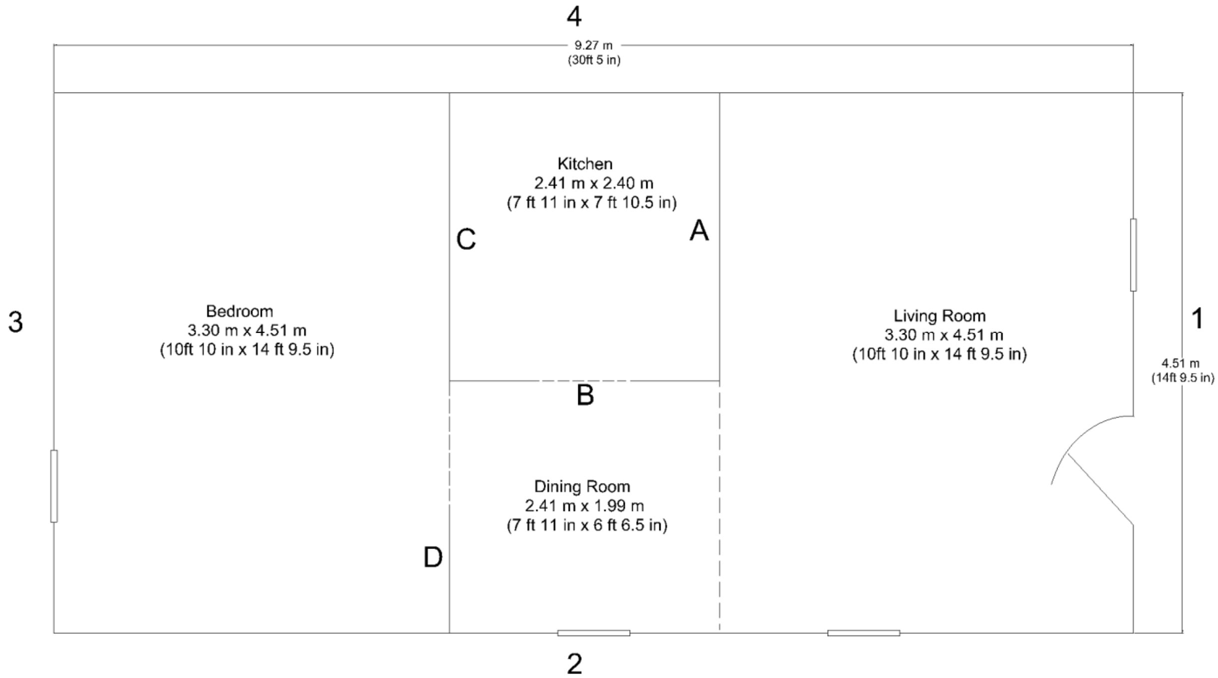

Figure A-1. Plan view with room and overall enclosure dimensions. Bold letters and numbers indicate naming conventions for exterior and interior walls. All dimensions given reflect interior dimensions.

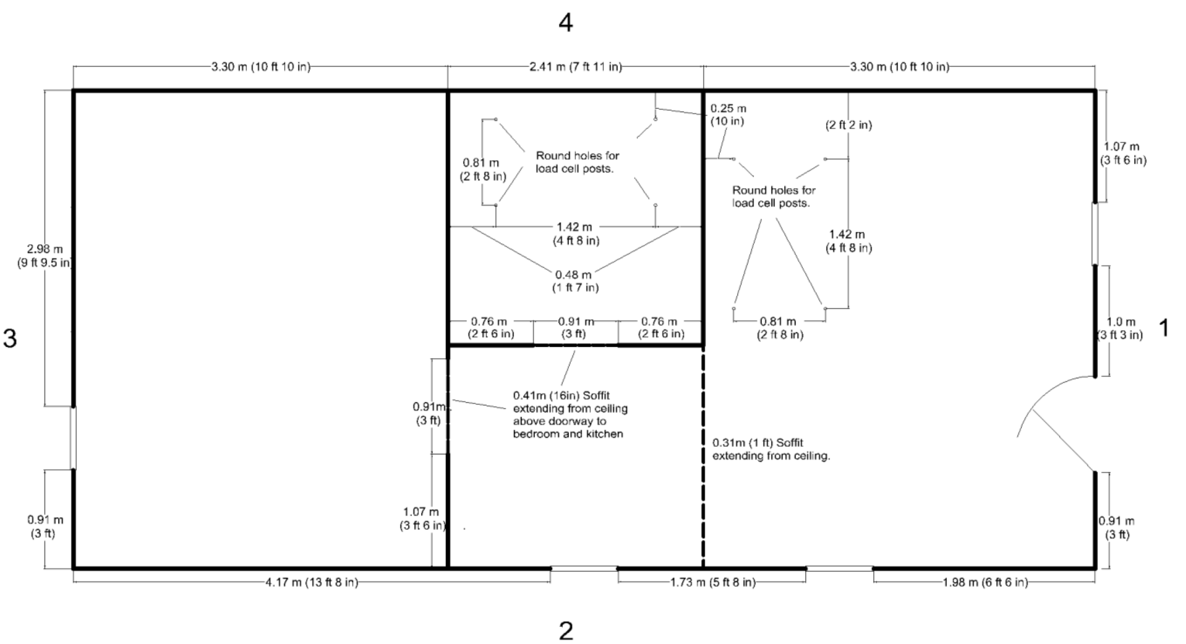

Figure A-2. Plan view with detailed enclosure dimensions.

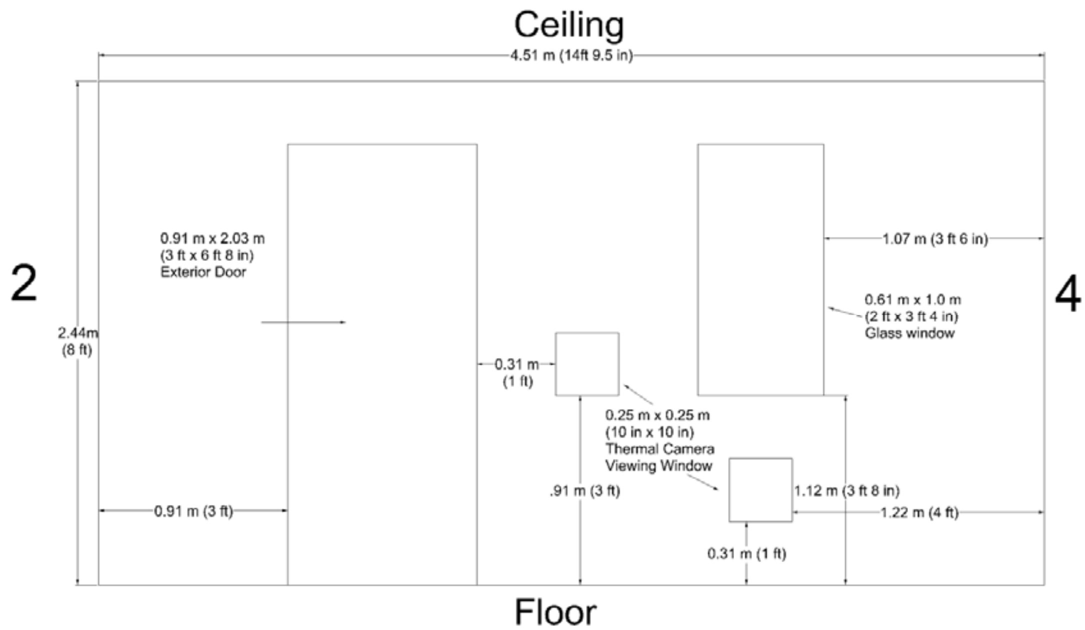

Figure A-3. Elevation view of Wall 1

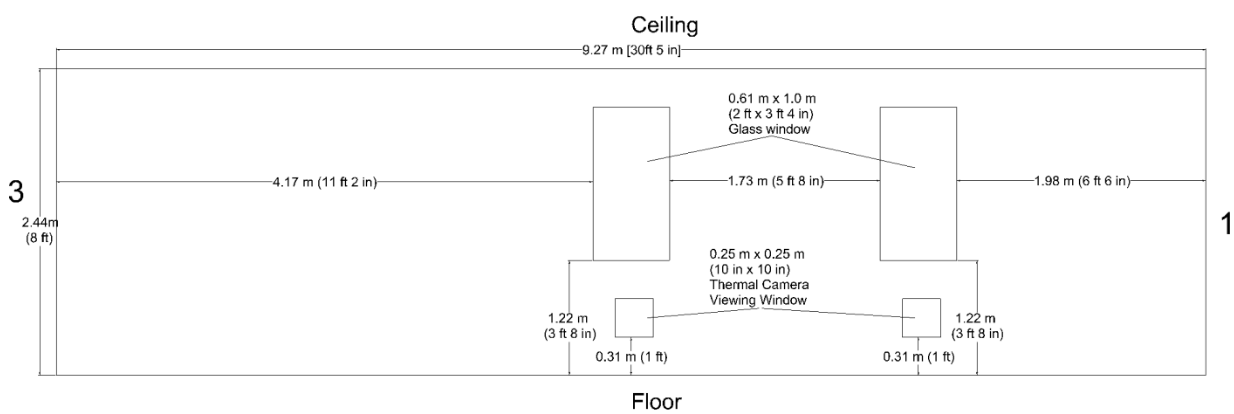

Figure A-4. Elevation View of Wall 2

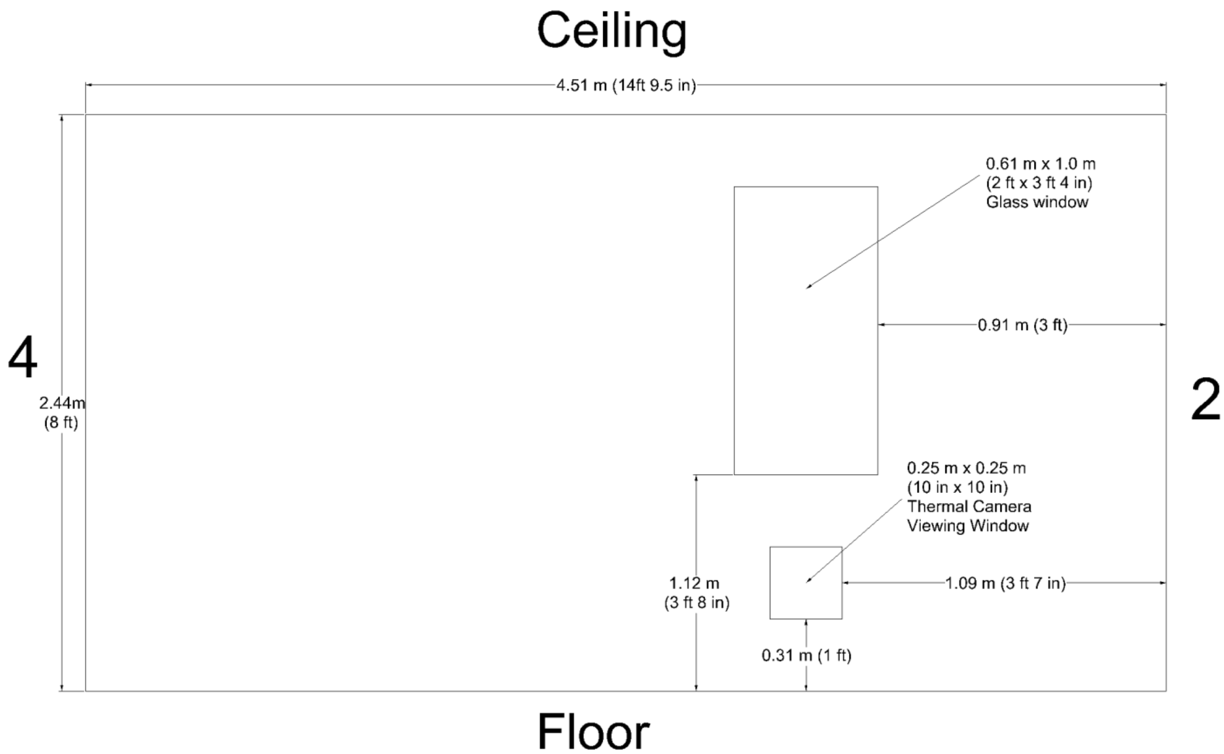

Figure A-5. Elevation View of Wall 3

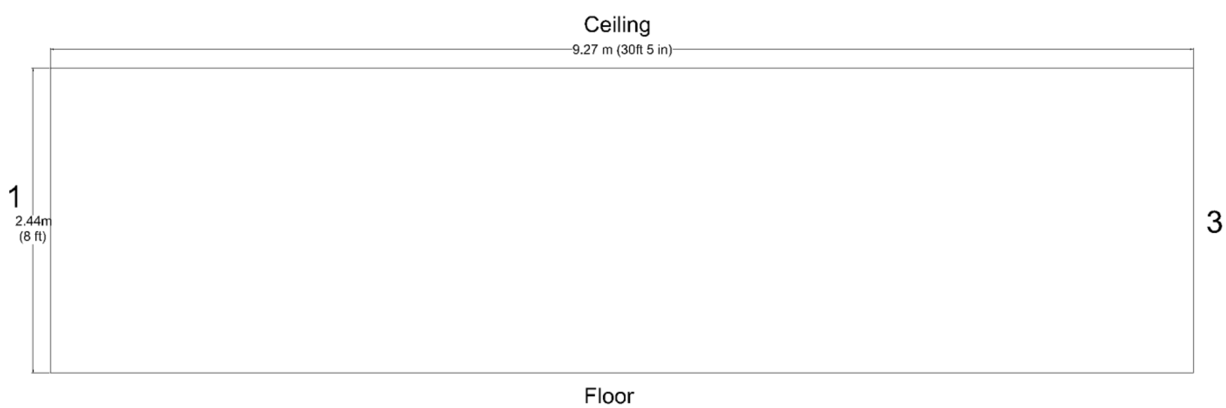

Figure A-6. Elevation view of Wall 4

APPENDIX B

SMOKE ALARM DATA

During some of the tests, smoke alarms were installed in the enclosure. Smoke alarms from three different manufacturers were used. These manufacturers are referred to as manufacturers 1, 2, and 3. From each of the manufacturers, an ionization, photoelectric, and combination ionization/photoelectric alarm was used, with the exception of manufacturer 3, which did not have a combination unit. The smoke alarms were given a naming convention as seen in Table B-1.

The smoke alarms were placed in arrays in the living room, dining room, and bedroom. For each test, two out of the three arrays were used, depending on the fire location. In addition to the smoke alarms, ODMs and three TCs were placed at each array location. The TCs were equally spaced along the array, and each TC characterized conditions for 2 to 3 alarms. Depending on the length of the array, one or two ODMs were used, with each smoke alarm characterized by one ODM. The placements of the smoke alarms, ODMs and TCs can be seen in Figure B-1. An outline of the array can be seen in Figure B-2, and the ODM and TC that corresponds to each smoke alarm can be seen in Table B-1. A photo of a smoke alarm array can be seen in Figure B-3. When referring to an alarm or TC, the instrument will be named by the array number, then the instrument number. For instance, the manufacturer 1 ionization detector in array 2 will be referred to as 2-1i.

Table B-1. Smoke Alarm Naming Convention

Manufacturer	Type	Name	TC	ODM
1	Ionization	1i	1	1
1	Photoelectric	1p	1	1
1	Combination	1c	1	1
2	Ionization	2i	2	2 (1)
2	Photoelectric	2p	2	2 (1)
2	Combination	2c	2	2 (1)
3	Ionization	3i	3	1
3	Photoelectric	3p	3	1

Note: For array 2, only one ODM was used (ODM 1)

Each smoke alarm was powered via a 9V battery. In all but one smoke alarm, an interconnect wire was used to monitor the alarm signal via connection to the DAQ. Upon activation, a signal of approximately 9V was sent through the wire connection to the DAQ to signal activation. Smoke alarm 2c did not have an interconnect option. For this smoke alarm, activation was recorded using acoustic monitoring. The monitors used were located outside of the enclosure on the ceiling of the structure. Each acoustic monitor possessed a directional microphone capable of detecting a specific alarm activation. Approximately 0.61 m (2 ft) of 6.35 mm (0.25 in.) copper tubing was used to transmit the alarm signal from the smoke alarm face to the acoustic monitor located outside the enclosure. The tubing was positioned approximately 12.2 mm (0.5 in) below the face of each active alarm. The tubing was located such that it would not interfere with the impinging ceiling jet (see Figure B-4).

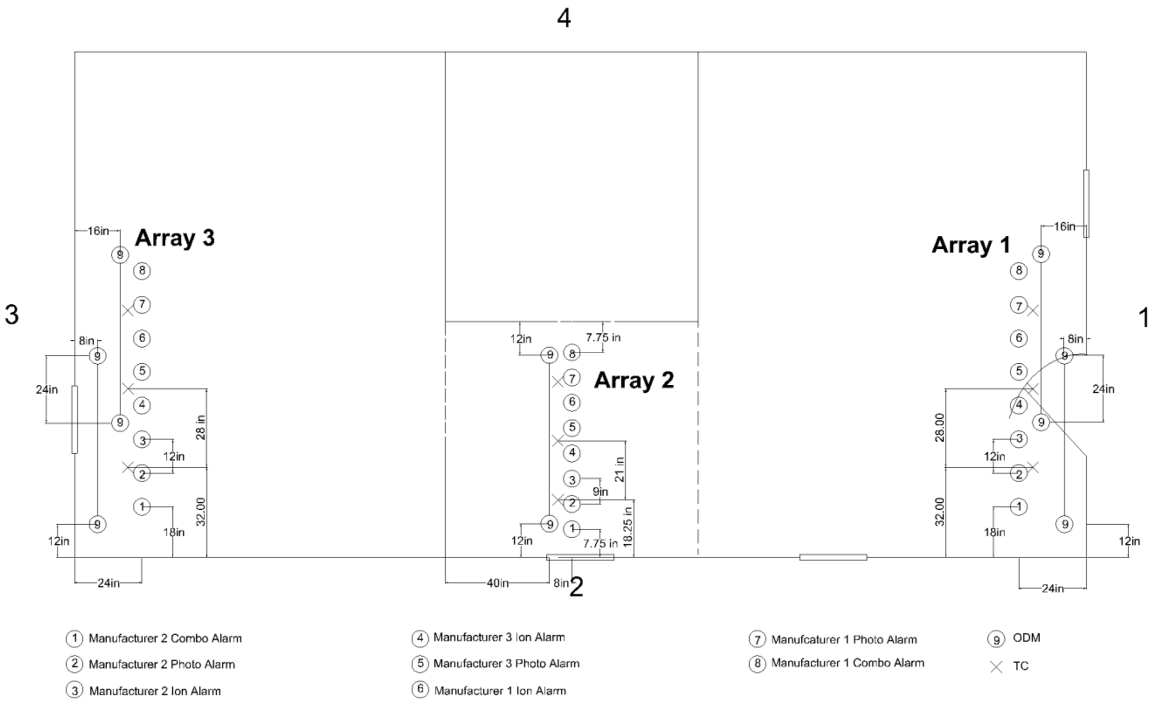

Figure B-1. Smoke alarm locations and placement

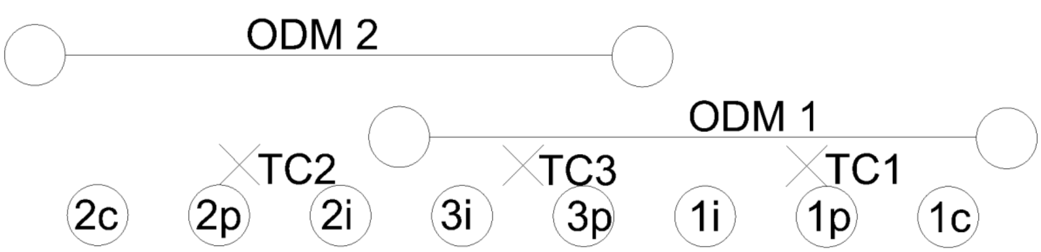

Figure B-2. Typical smoke alarm array layout

Note: ODM 2 and alarm 2c were always closest to wall 2. For Array 2, only one ODM was used (ODM1)

Figure B-3. Photo of smoke alarm array 2

Figure B-4. Acoustic monitor tubing placement

The data accumulated from these tests is show in Table B-2. Each smoke alarm activation time is given, as well as a corresponding temperature and optical density per meter at that time.

Table B-2. Smoke alarm activation times and corresponding temperature and optical density

SM1 - Smoldering Batting																
Cluster Location	Array 1								Array 2							
Alarm ID	1i	2i	3i	1p	2p	3p	1c	2c	1i	2i	3i	1p	2p	3p	1c	2c
Time to Activation (min)	62.6	68.0	73.9	47.8	46.6	67.6	42.8	42.0	26.3	30.6	30.4	24.6	28.4	25.5	22.0	29.0
Temperature at Activation (C)	26.5	29.3	29.5	26.3	29.2	29.3	26.4	29.1	26.5	26.2	26.6	26.5	26.2	26.3	26.2	26.2
OD/m at Activation (m^{-1})	0.10	0.17	0.22	0.04	0.04	0.16	0.02	0.02	0.16	0.17	0.17	0.13	0.14	0.14	0.13	0.16
SM2 - Smoldering Sofa 1																
Cluster Location	Array 2								Array 3							
Alarm ID	1i	2i	3i	1p	2p	3p	1c	2c	1i	2i	3i	1p	2p	3p	1c	2c
Time to Activation (min)	38.7	25.3	DNA	15.7	18.1	19.2	15.5	15.9	45.0	21.9	DNA	17.0	23.5	61.6	17.0	19.0
Temperature at Activation (C)	26.1	25.4	DNA	26.0	25.4	25.8	26.0	25.3	26.0	25.6	DNA	25.6	25.6	26.0	25.6	25.4
OD/m at Activation (m^{-1})	0.09	0.03	DNA	0.01	0.01	0.01	0.01	0.01	0.14	0.04	DNA	0.01	0.04	0.16	0.01	0.04
SM3 - Smoldering Sofa 2																
Cluster Location	Array 2								Array 3							
Alarm ID	1i	2i	3i	1p	2p	3p	1c	2c	1i	2i	3i	1p	2p	3p	1c	2c
Time to Activation (min)	25.7	16.0	38.7	15.4	16.0	15.9	14.6	15.3	29.1	14.3	42.0	15.4	16.7	21.4	15.7	12.4
Temperature at Activation (C)	26.9	26.4	27.4	26.9	26.4	26.8	27.0	26.4	26.8	26.5	27.0	26.6	26.6	26.6	26.6	26.4
OD/m at Activation (m^{-1})	0.05	0.02	0.28	0.01	0.02	0.02	0.01	0.01	0.03	0.01	0.14	0.01	0.01	0.01	0.02	0.01
SM4 - Smoldering Sofa 3																
Cluster Location	Array 2								Array 3							
Alarm ID	1i	2i	3i	1p	2p	3p	1c	2c	1i	2i	3i	1p	2p	3p	1c	2c
Time to Activation (min)	14.2	N/P	20.3	12.3	12.5	13.1	13.8	11.0	25.9	N/P	36.4	14.4	17.6	15.1	14.1	N/D
Temperature at Activation (C)	24.3	N/P	24.6	24.1	24.3	24.3	24.2	24.4	24.6	N/P	24.7	24.3	24.0	24.3	24.5	N/D
OD/m at Activation (m^{-1})	0.08	N/P	0.13	0.05	0.06	0.08	0.07	0.02	0.11	N/P	0.19	0.04	0.05	0.04	0.04	N/D
S1 - Flaming Sofa																
Cluster Location	Array 2								Array 3							
Alarm ID	1i	2i	3i	1p	2p	3p	1c	2c	1i	2i	3i	1p	2p	3p	1c	2c
Time to Activation (min)	8.3	8.3	9.2	11.8	11.8	12.0	8.8	9.2	9.7	9.5	10.4	12.3	12.1	12.2	10.7	9.6
Temperature at Activation (C)	28.6	27.5	29.6	38.2	36.0	42.9	29.2	28.6	27.7	27.8	28.2	33.5	32.8	32.9	28.3	27.8
OD/m at Activation (m^{-1})	0.00	0.00	0.00	0.08	0.08	0.21	0.00	0.00	0.06	0.00	0.05	0.26	0.08	0.18	0.07	0.00
CH1 - Flaming High Cabinet																
Cluster Location	Array 1								Array 3							
Alarm ID	1i	2i	3i	1p	2p	3p	1c	2c	1i	2i	3i	1p	2p	3p	1c	2c
Time to Activation (min)	12.0	10.8	12.0	12.5	11.1	11.8	12.5	11.1	13.0	11.8	12.2	12.2	12.3	12.9	12.4	12.1
Temperature at Activation (C)	24.7	27.0	26.4	25.7	26.9	26.3	25.7	26.9	26.3	25.0	25.3	25.6	25.3	26.1	25.7	25.1
OD/m at Activation (m^{-1})	0.14	0.02	0.14	0.40	0.04	0.07	0.40	0.04	0.23	0.04	0.05	0.05	0.08	0.19	0.10	0.06
CH2 - Flaming High Cabinet																
Cluster Location	Array 1								Array 3							
Alarm ID	1i	2i	3i	1p	2p	3p	1c	2c	1i	2i	3i	1p	2p	3p	1c	2c
Time to Activation (min)	13.0	12.9	13.1	13.8	12.7	13.0	14.2	N/D	13.8	13.1	13.3	14.3	N/P	13.7	12.8	N/D
Temperature at Activation (C)	25.5	27.9	27.4	26.7	28.0	27.3	27.3	N/D	26.9	25.8	26.1	27.6	N/P	26.6	26.2	N/D
OD/m at Activation (m^{-1})	0.09	0.10	0.09	0.32	0.04	0.09	0.51	N/D	0.16	0.04	0.07	0.21	N/P	0.13	0.03	N/D

DNA - Did not alarm

N/P - Alarm not present at this location during test

N/D - Activation could not be determined due to instrument malfunction

Note: ODM 3-1 malfunctioned during test SM4. ODM 3-2 was used for all optical density measurements for array 3.

APPENDIX C

FIRE POINT THEORY LOWER OXYGEN LIMIT ANALYSIS

The results of this study were used to validate the Beyler unified model of fire suppression based on the fire point equation to calculate the lower oxygen index (LOI) (Beyler, 1992). Using this method, the critical oxygen concentration value was determined by a modeling equation that takes into account heat capacity and dilution effects by using material properties and experimental data. The fire point theory was implemented via the following equations:

$$\phi_o = \kappa\left(1 - \frac{c_p(T_{AFT}(SL) - T_O)}{\Delta H_R(O_2)Y_{O2;\infty}}\right) \qquad \text{Equation 11 from Beyler}$$

$$\phi = \frac{\phi_o - \kappa Y_{ext}\left(1 + \frac{\Delta c_p(T_{AFT}(SL) - T_O)}{\Delta H_R(O_2)Y_{O2;\infty}}\right)}{1 - Y_{ext}} \qquad \text{Equation 12 from Beyler}$$

$$(\phi\Delta H_c - L_V)\frac{h}{c_p}\ln\left(1 + \frac{Y_{O2}\Delta H_R(O_2)}{\phi\Delta H_c}\right) + \dot{Q}_E'' - \dot{Q}_L'' - \dot{Q}_W'' = 0 \qquad \text{Equation 5 from Beyler}$$

where:
κ=0.6

$T_{AFT}(SL)$ = the adiabatic flame temperature at the stoichiometric limit (approximately 1700 K)

$\Delta H_R(O_2)$ = 13 kJ/g

Y_{O2} and $Y_{O2;\infty}$ = the oxygen mass fractions in the room and in ambient conditions, respectively

Y_{ext} = the concentration of the suppressing agent (taken to be CO_2),

L_V = the heat of gasification

h = the convective heat transfer coefficient

Q_E" = externally applied heat flux (taken as the heat flux from the upper layer, measured by vertically oriented heat flux gauges mounted in the floor)

Q_L" = heat losses (only radiative heat losses were considered, and were calculated based on the ignition temperature of the material and the average room temperature)

Q_W" = heat loss due to water (considered to be negligible)

ϕ = fraction of heat generated which must be lost to cause the flame to be quenched

ϕ_o= value of ϕ when Y_{ext} = 0

Equation 11 was solved first and substituted into Equation 12. Once a value of ϕ was known, that value was used in Equation 5. All values were known for Equation 5 with the exception of Y_{O2}, which is the value of the critical oxygen needed to burn, or the LOI.

There were a number of uncertainties in these calculations. The largest uncertainty was the value of h, the convective heat transfer coefficient. No instrumentation was present to aid in the calculation of a value for h. A range of values of 5-25 $W/(m^2K)$ is given by Drysdale (Drysdale, 1999) for free convection. Since the coefficient could not be calculated, a heat flux was determined that yielded general agreement with the LOI values determined experimentally from the tests in this study (see Section 6.2). A convective heat transfer coefficient of 8 was determined for the sofa fires, and a coefficient of 10.5 was determined for the cabinet fires to yield comparable values between the Beyler model and the experimental results. Both of these coefficients are within the range suggested by Drysdale. Another uncertainty is the assumption that CO_2 was the only suppressing agent. A third uncertainty was the use of the floor level vertical heat flux gauges for the radiative feedback term. The difference in height between the floor and the fuel source could affect the value of the heat flux.

Calculations of a LOI were done for each test that self suppressed. These values were then compared to the values determined experimentally via an upper layer temperature method and an upper layer oxygen method. These values are shown in Table C-1 and Table C-2. Overall, the results from the fire point theory analysis were fairly consistent within a fuel type (sofa and cabinets). Overall, the fire point theory calculated values are in good agreement with the values that were determined experimentally. There are a few exceptions where the fire point calculated LOI is drastically lower than the values determined from the measured oxygen concentrations. These exceptions occur when there were high temperatures and heat fluxes, and could be a result of the method used to calculate the radiative loss term.

Table C-1. Comparison of Calculated LOI to Experimental LOI Using the Temperature Method.

	Time (min)	CO_2 mass fraction	Temp (K)	Heat Flux (kW/m^2)	Experimental O_2 (%)	Calculated O_2 (%)
S1	15.78	0.005	418	1.00	20.33	18.92
S3	14.97	0.034	628	4.72	17.73	1.66
S4	2.97	0.024	457	0.99	18.16	18.14
CL1	19.90	0.03	471.00	1.92	15.48	11.34
	91.50	0.05	340.00	0.14	16.34	17.39
	93.90	0.05	571.00	2.54	15.72	6.95
CL2	18.45	0.02	588.00	6.17	19.16	1.46
	54.00	0.04	350.00	0.30	16.83	16.71
	62.83	0.05	575.00	4.32	16.00	4.39
CH1	21.23	0.07	513.00	2.22	16.71	10.12
	80.00	0.04	328.00	0.26	16.64	17.08
	93.27	0.05	375.00	0.75	15.84	15.82
	129.70	0.05	339.00	0.34	15.88	16.96
	135.72	0.05	362.00	0.55	15.95	16.34
CH2	19.43	0.022	454	2.33	18.74	11.06
	27.50	0.047	370	0.28	16.19	16.62
	34.17	0.047	378	0.31	16.28	16.44
	96.50	0.029	334	0.13	18.15	16.87
	106.85	0.053	449	1.35	16.19	13.29

Table C-2. Comparison of Calculated LOI to Experimental LOI Using the Oxygen Method

	Time (min)	CO_2 mass fraction	Temp (K)	Heat Flux (kW/m^2)	Experimental O_2 (%)	Calculated O_2 (%)
S1	16.53	0.012	413	1.03	19.43	19.20
S3	14.80	0.028	587	4.95	19.25	3.93
S4						
CL1	19.42	0.045	476	1.48	16.04	12.14
	91.02	0.046	340	0.12	16.34	17.30
	93.73	0.052	533	1.96	15.9	9.48
CL2	18.55	0.022	593	5.79	19.1	1.67
	58.03	0.040	353	0.32	16.95	16.60
	62.98	0.055	587	4.86	15.76	3.16
CH1	20.67	0.041	502	2.40	16.39	9.83
	73.07	0.043	327	0.25	16.38	17.13
	91.13	0.046	371	0.58	16.16	16.06
	130.13	0.047	339	0.36	15.89	16.92
	138.58	0.055	365	0.59	15.48	16.40
CH2	38.73	0.046	372	0.29	16.39	16.54
	96.00	0.029	334	0.14	18.1	16.85
	107.28	0.056	438	1.02	15.77	14.20

APPENDIX D

VENT FLOWS

D.1Velocity and Mass Flow Rate

The vent flow velocity and mass flow rate were determined for all tests with window ventilation, with the exception of test CH2 (high cabinet half open window) which had an instrumentation malfunction. The velocity and mass flow rate were determined in accordance with a method described by Emmons (Emmons, 2008) that utilizes a single differential pressure measurement and two sets of temperature array measurements.

A slight deviation was taken when using the method outlined by Emmons. For the calculation of pressure difference, instead of using density gradients based on temperature measurements, the pressure transducers located in the bedroom were used to establish a pressure difference across the vent. The pressure transducer data was plotted against height, and a linear fit was applied across the height of the vent. From this linear fit, and approximate pressure difference was determined for any height in the vent. An example of this procedure is show in Figure D-1. A full set of pressure data can be found in Appendix E.

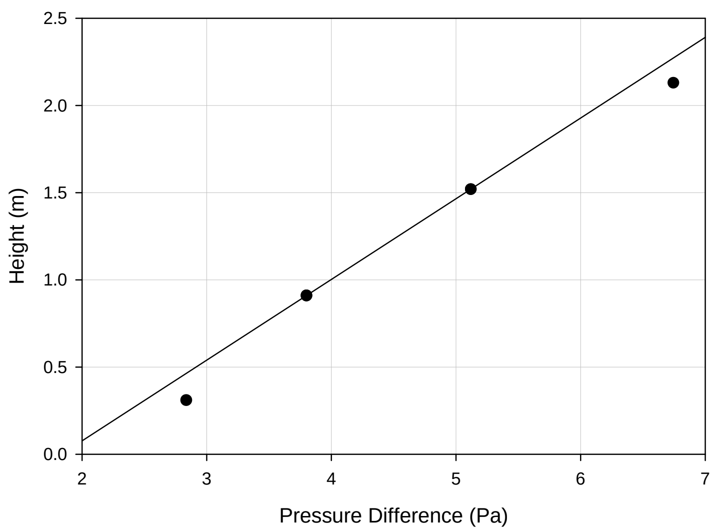

Figure D-1. Pressure difference determination for test S3 at 14.16 seconds

The window vent had a TC tree at the plane of the vent, consisting of four to eight TCs, depending on the height of the vent. Section 4.1.3 outlines the positioning of these TCs. In general the temperature was measured about every 5-7 cm. These temperature measurements were used to determine the density of the gases in the window as a function of height.

The pressure differences and densities were then used to calculate the velocity, per the following equation, at the heights of the TCs at three times during the test.

$$V = \sqrt{\frac{2\Delta p}{\rho}}$$

The three times that were used for determining the velocities were 50% of the peak heat release rate, at the peak heat release rate, and a third point at least 10 minutes after the fire had become vitiated, or the end of the test in cases where vitiation did not occur. Based on an integration of the gas velocity and density over the height of the vent, the mass flow rate was calculated for inflow and outflow through the vent. These calculations were done as follows:

Flow Out:

$$\dot{m} = C \int_{h_n}^{h_t} \rho b V \, dy$$

Flow In:

$$\dot{m} = C \int_{h_b}^{h_n} \rho b V \, dy$$

In the above calculations, b is the width of the vent (0.61 m (2 ft)), C is the flow coefficient (0.68), Δp is the pressure difference at a specific height, h_b is the height at the base of the vent, h_n is the height of the neutral plane, and h_t, is the height of the top of the vent. Tables D-1, D-2 and D-3 show the velocities as a function of height and the total inflow and outflow for the time sampled for each test. Positive velocities represent flow out of the enclosure.

Table D-1. Velocities (m/s) and mass flow rates from tests with half open window

	S3			S4			CL2		
Height (m)	14.16 min	15.00 min	28.33 min	1.12 min	2.48 min	28.33 min	16.66 min	18.33 min	33.33 min
1.33	3.11	3.52	0.35	3.57	1.07	-0.40	1.86	1.97	0.48
1.28	3.03	3.34	0.10	3.47	0.88	-0.45	1.82	1.84	0.34
1.23	2.97	3.19	-0.31	3.41	0.65	-0.49	1.79	1.74	-0.06
1.18	2.92	3.05	-0.45	3.36	0.29	-0.53	1.75	1.63	-0.33
Mass Flow In (kg/s)	0.00	0.00	0.01	0.00	0.00	0.10	0.00	0.00	0.01
Mass Flow Out (kg/s)	0.48	0.42	0.01	0.59	0.13	0.00	0.31	0.28	0.02

Table D-2. Velocities (m/s) and mass flow rates from tests with full open window

	S2	
Height (m)	14.16 min	15.9 min
1.51	0.99	1.36
1.46	0.94	1.15
1.40	0.89	0.85
1.34	0.84	0.43
1.28	0.79	-0.51
1.21	0.72	-0.86
Mass Flow In (kg/s)	0.00	0.04
Mass Flow Out (kg/s)	0.48	0.17

Note: Test was stopped at ~15.9 minutes

Table D-3. Velocities (m/s) and mass flow rates from tests with window removed

	CH3		
Height (m)	18.33 min	21.67 min	29.50 min
2.04	0.38	1.36	1.70
1.92	0.26	1.21	1.50
1.79	-0.10	1.05	1.29
1.66	-0.29	0.85	1.05
1.54	-0.39	0.61	0.75
1.41	-0.48	0.23	0.28
1.28	-0.55	-0.51	-0.56
1.16	-0.61	-0.73	-0.82
Mass Flow In (kg/s)	0.31	0.05	0.06
Mass Flow Out (kg/s)	0.06	0.91	0.78

Note: Test was stopped at ~29.5 minutes

General Findings

- Start of inflow
    - Half open windows – not until after peak
    - Full open window – some during peak
    - No window – throughout test
- Mass flow in rarely equals mass flow out (some cases in far field)
- Mass flow out generally always higher
- Neutral plane in long term very similar across all ventilation sizes (approx 1.2 - 1.4 m)
- During burning, sofa tests had relatively higher velocities and mass flow rates (compare S3 to CL2)

APPENDIX E

PRESSURE DATA

Pressure measurements were taken at twelve locations in the enclosure. These locations were at 0.31 m, 0.91 m, 1.52 m, and 2.13 m elevations in the living room, kitchen, and bedroom. Section 4.3 has more detail on the pressure transducers and locations. The data from these measurements is shown below. The data is presented by pressure differentials (with respect to ambient) in the room of origin at all four elevations, and a comparison of pressure differentials between all three rooms at the 1.52 m elevation. Although the pressure transducers had a max range of 133.32 Pa, due to the data acquisition system setup, the maximum range of the measurements was 28 Pa. In tests S1, S3, CL1, and CH1 (Figures E-1, E-2, E-3, E-4, E-9, E-10, E-15 and E-16), the maximum pressure readings exceeded 28 Pa.

The data shows a few general trends. For one, as could be expected, the pressure is generally greater at higher elevations within the enclosure, where the hotter gasses are located. The pressure comparisons at 1.52 m show that for less ventilated scenarios (half open window and no ventilation) the pressure at that elevation is nearly the same between spaces. For tests with larger amounts of ventilation, the pressure in the room of origin is measurably greater at the 1.52 m elevation, consistent with the temperature profiles. The data also shows a distinction between tests with different amounts of ventilation. In tests that had no ventilation or half open window ventilation, there was an initial spike where the pressure quickly increased, then decreased every time the fire began to grow. After this initial spike, the pressures began to stabilize, with layering occurring (higher pressures higher in the enclosure). The tests with greater ventilation (window removed and open door) did not have this initial spike, and instead began gradually layering.

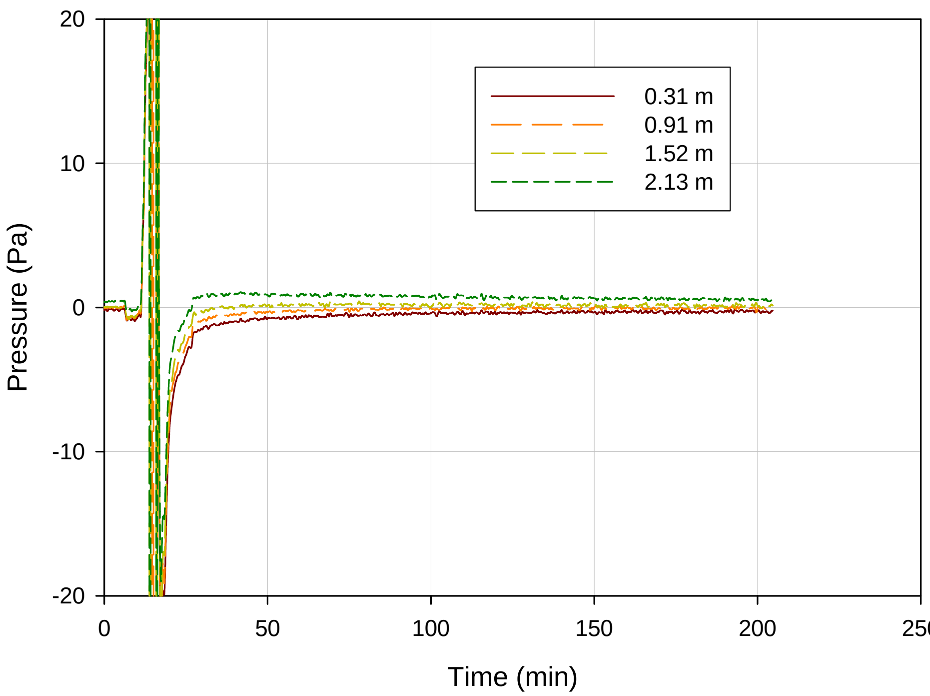

Figure E-1. Test S1 (sofa, no ventilation) pressures in room of origin (living room)

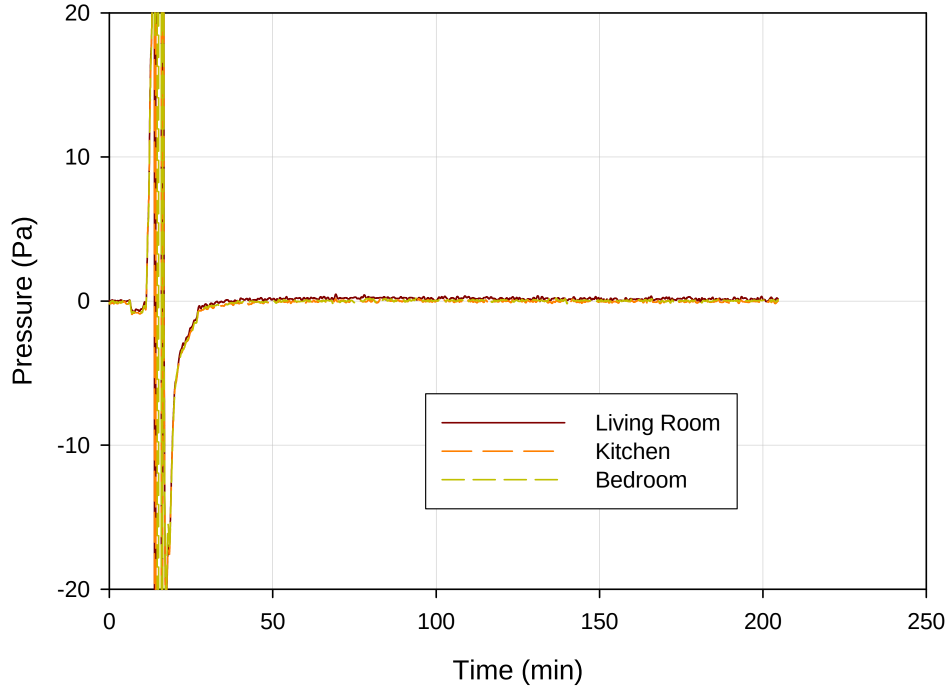

Figure E-2. Test S1 (sofa, no ventilation) pressure comparison at 1.52 m

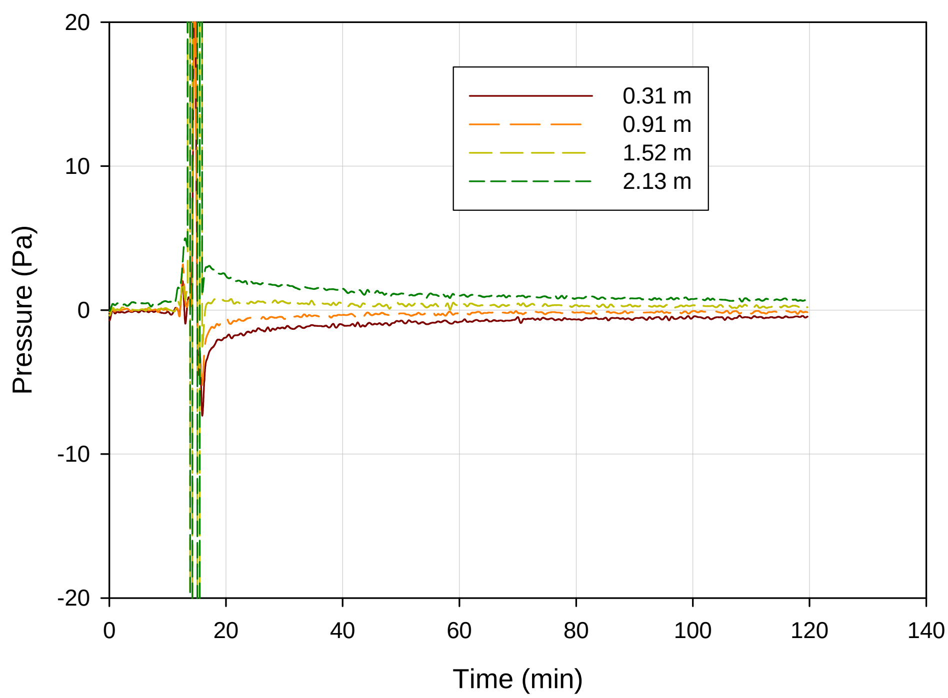

Figure E-3. Test S3 (sofa, half open window) pressures in room of origin (living room)

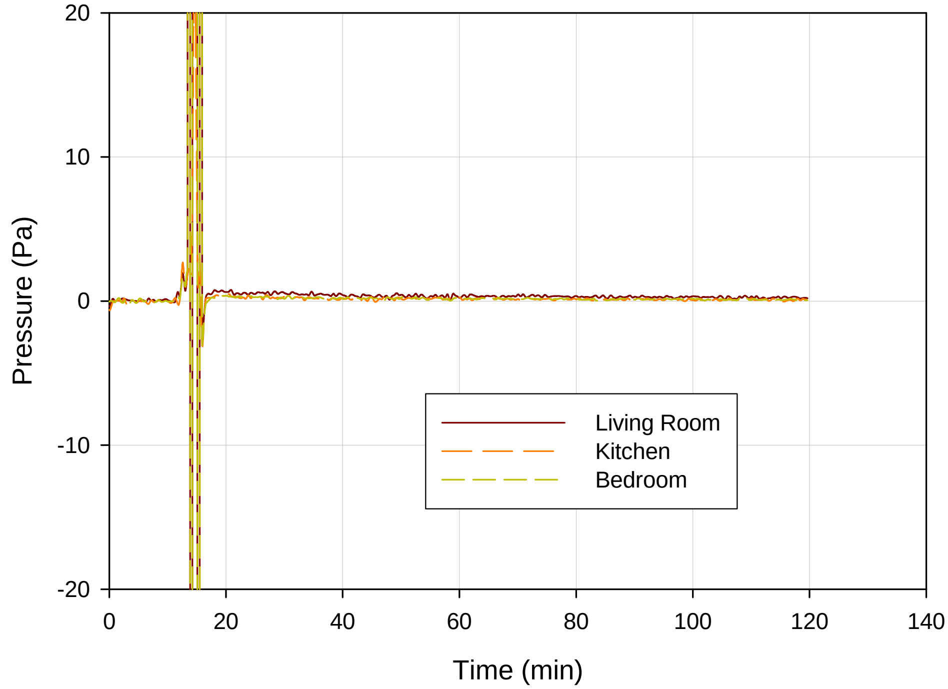

Figure E-4. Test S3 (sofa, half open window) pressure comparison at 1.52 m

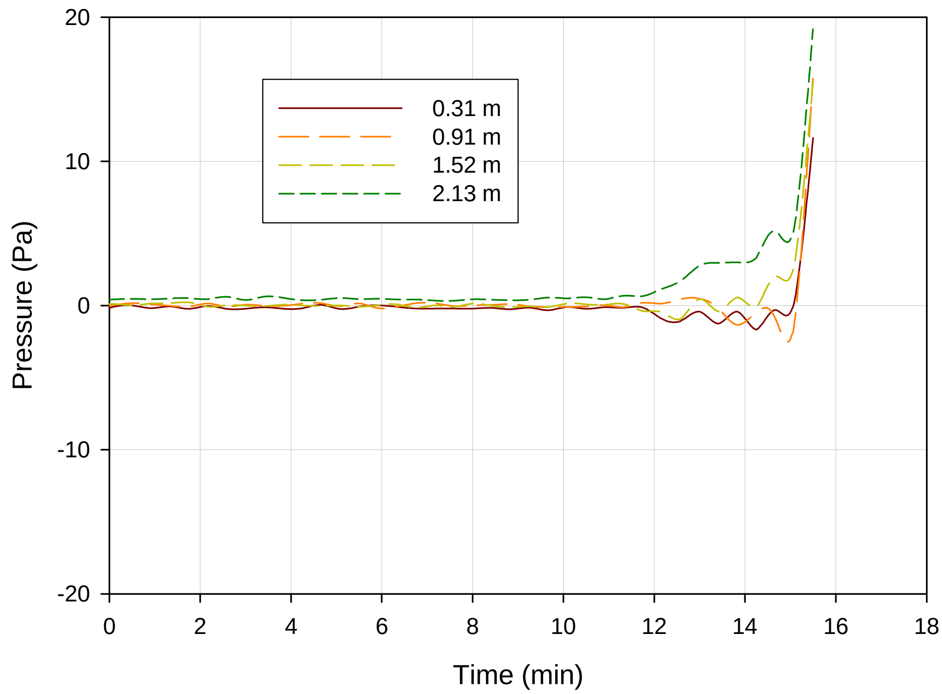

Figure E-5. Test S2 (sofa, full open window) pressures in room of origin (living room)

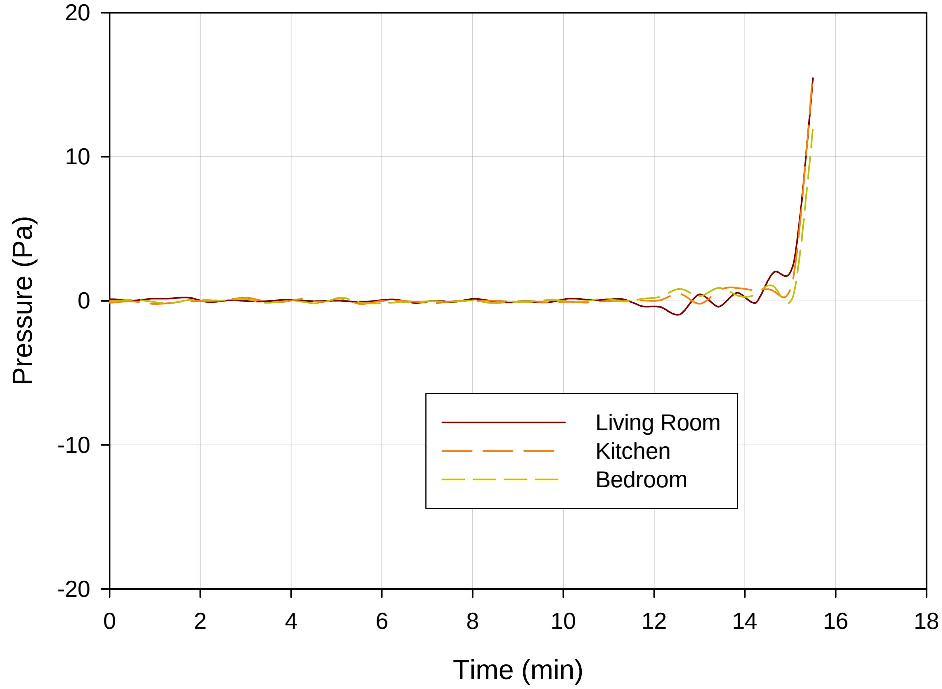

Figure E-6. Test S2 (sofa, full open window) pressure comparisons at 1.52 m

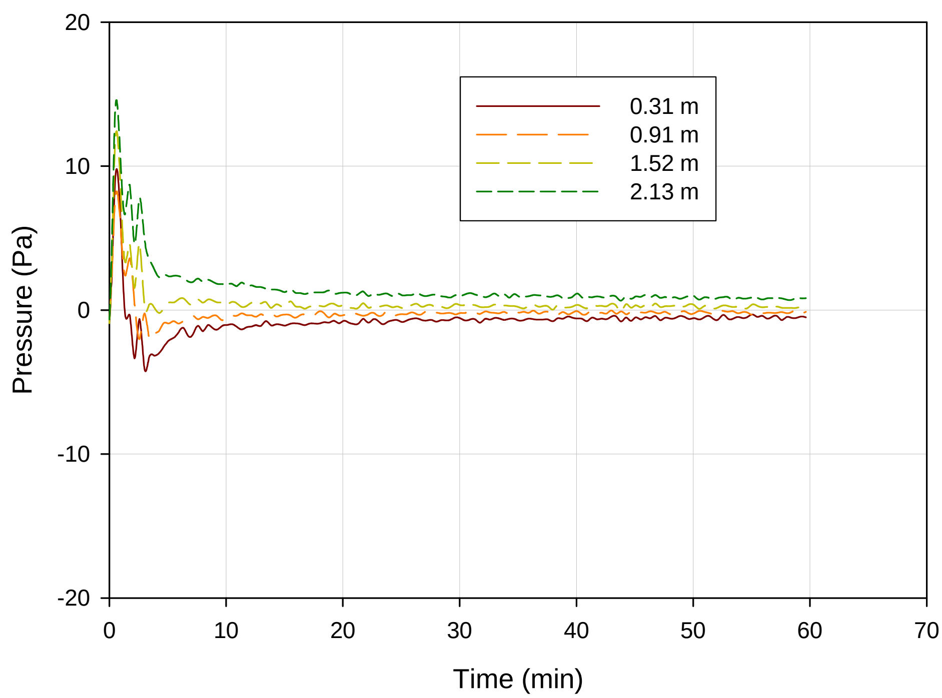

Figure E-7. Test S4 (sofa, accelerated, half open window) pressure in room of origin (living room)

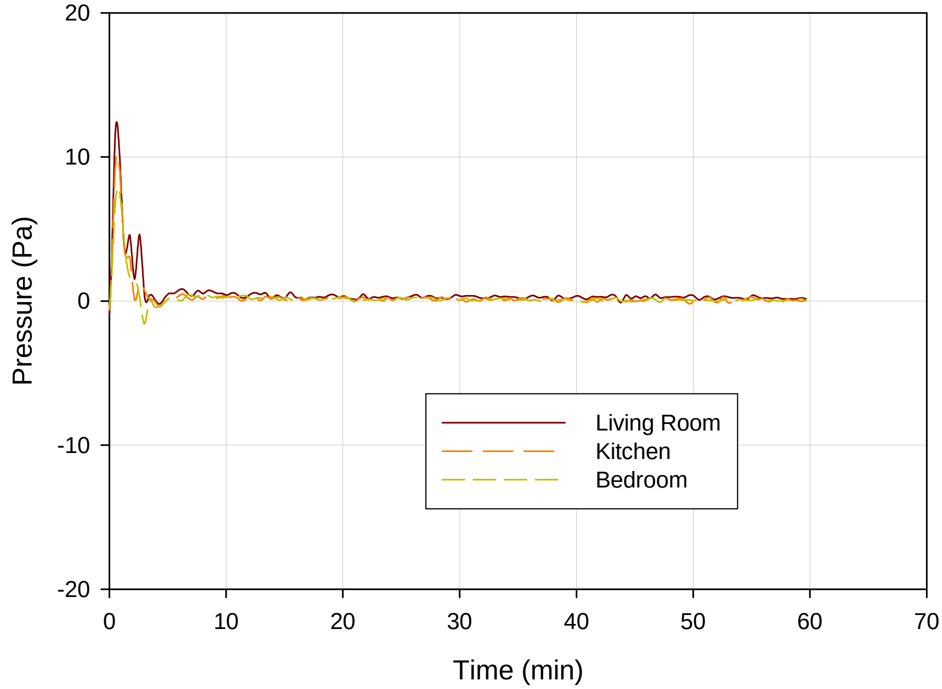

Figure E-8. Test S4 (sofa, accelerated, half open window) pressure comparisons at 1.52 m

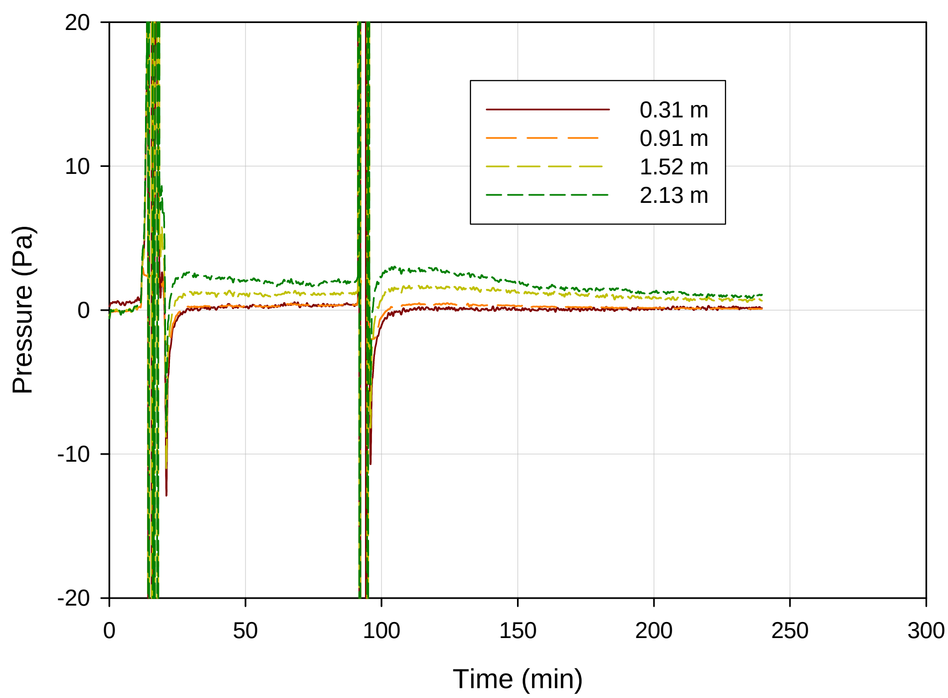

Figure E-9. Test CL1 (low cabinets, no ventilation) pressures in room of origin (kitchen)

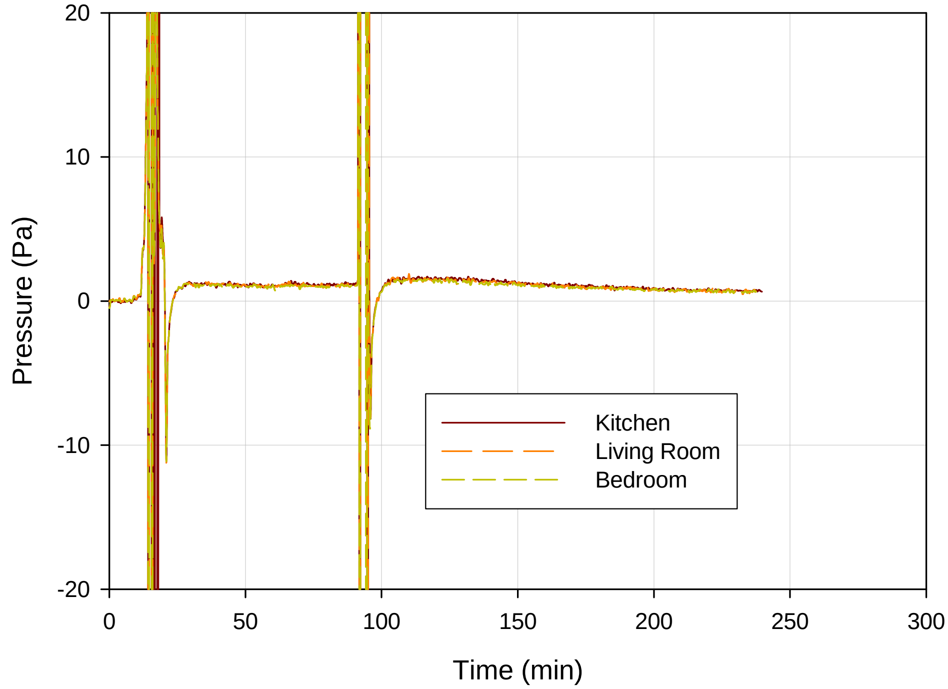

Figure E-10. Test CL1 (low cabinets, no ventilation) pressure comparisons at 1.52 m

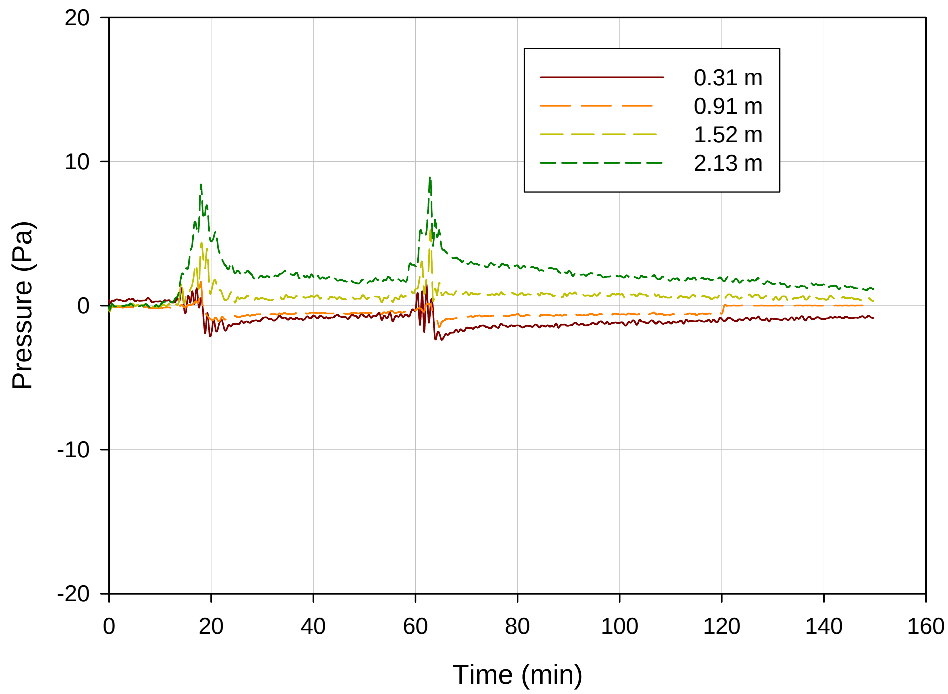

Figure E-11. Test CL2 (low cabinets, half open window) pressures in room of origin (kitchen)

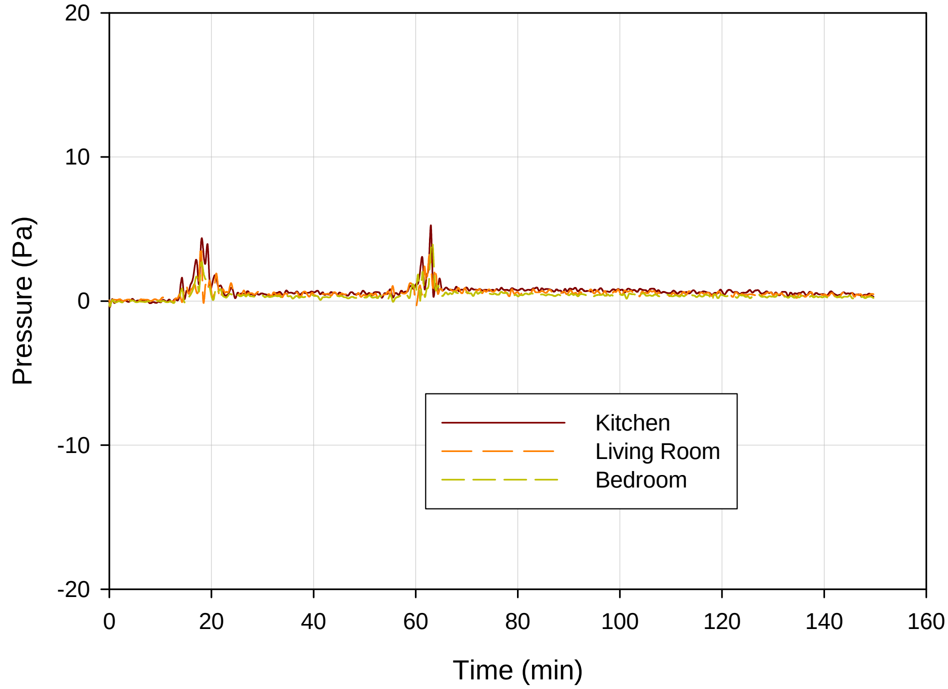

Figure E-12. Test CL2 (low cabinets, half open window) pressure comparison at 1.52 m

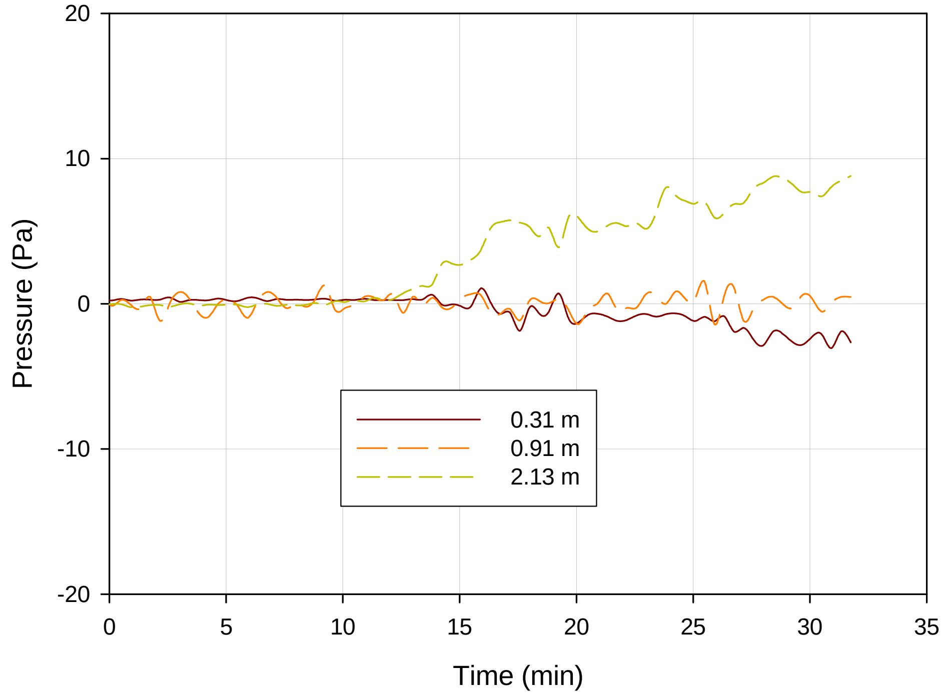

Figure E-13. Test CL3 (low cabinets, open door) pressures in room of origin (kitchen)
*The 1.52 m pressure transducer malfunctioned during this test

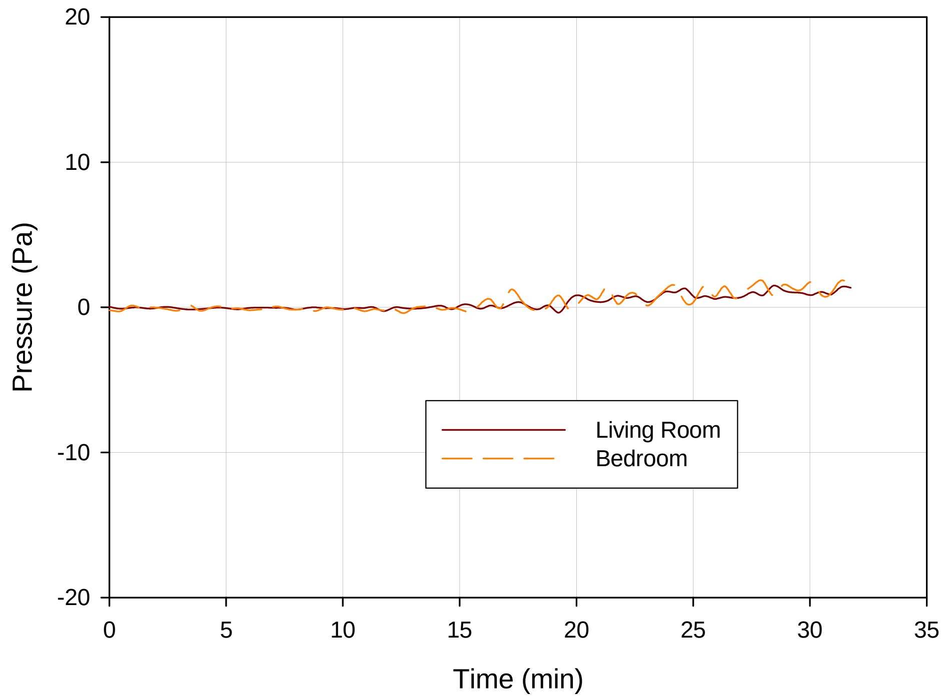

Figure E-14. Test CL3 (low cabinets, open door) pressure comparison at 1.52 m
*The 1.52 m pressure transducer in the kitchen malfunctioned during this test

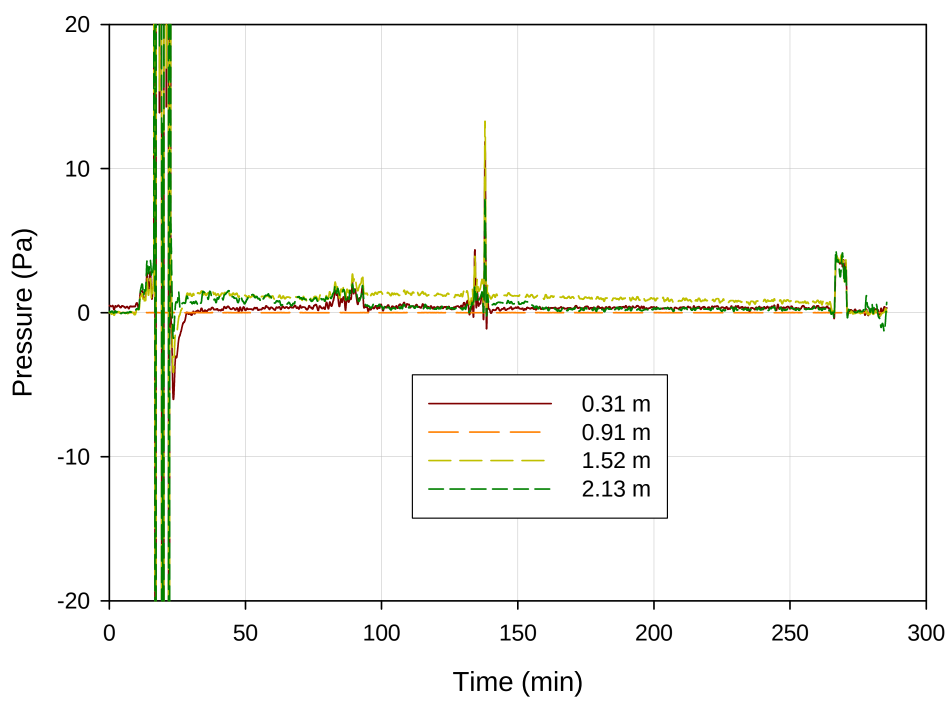

Figure E-15. Test CH1 (high cabinets, no ventilation) pressures in rom of origin (kitchen)

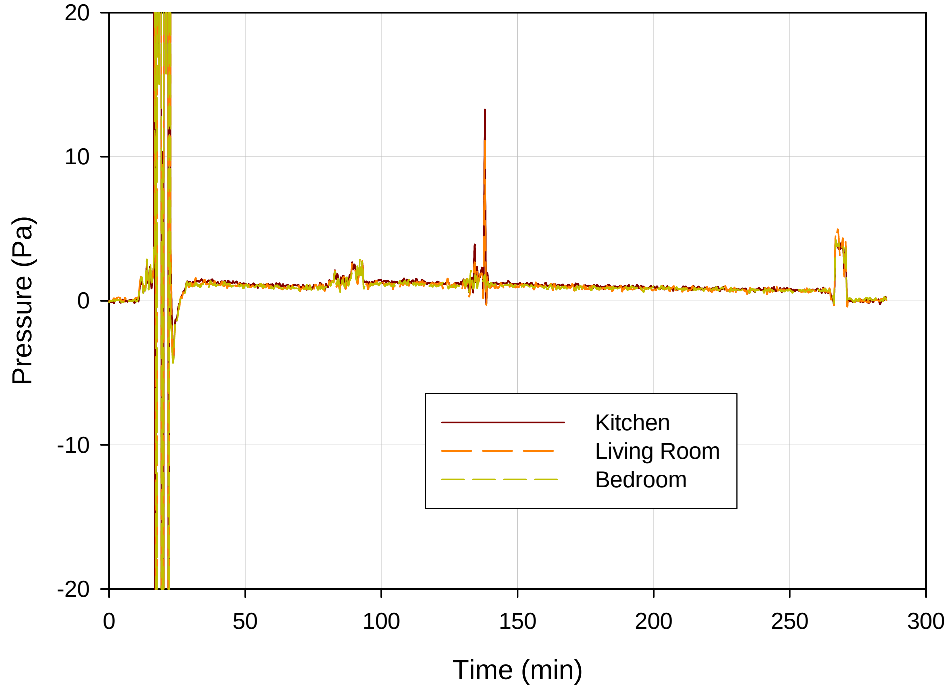

Figure E-16. Test CH1 (high cabinets, no ventilation) pressure comparison at 1.52 m

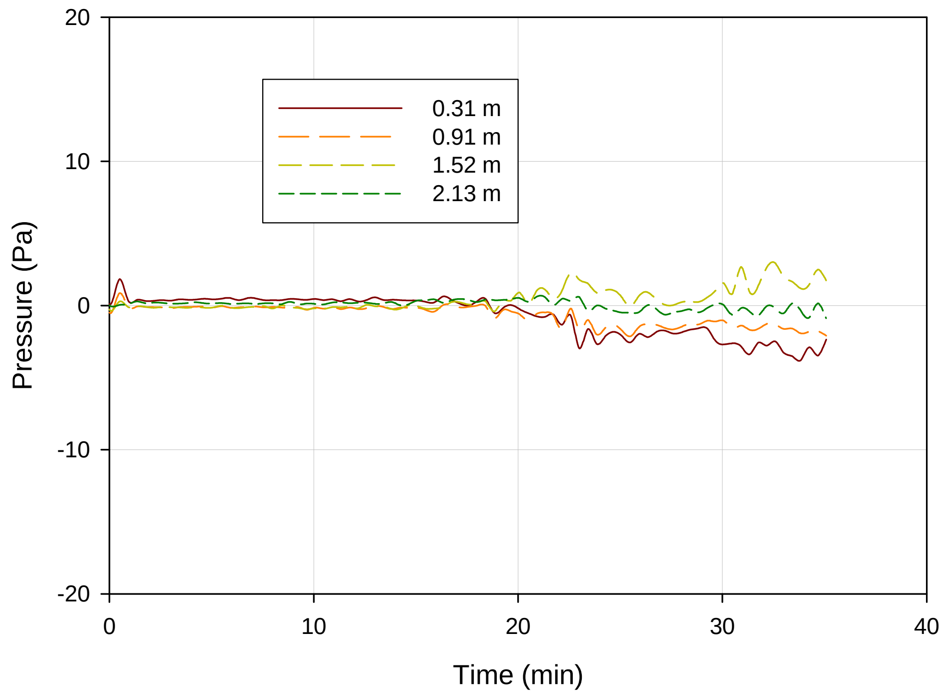

Figure E-17. Test CH3 (high cabinets, window removed) pressures in room of origin (kitchen)

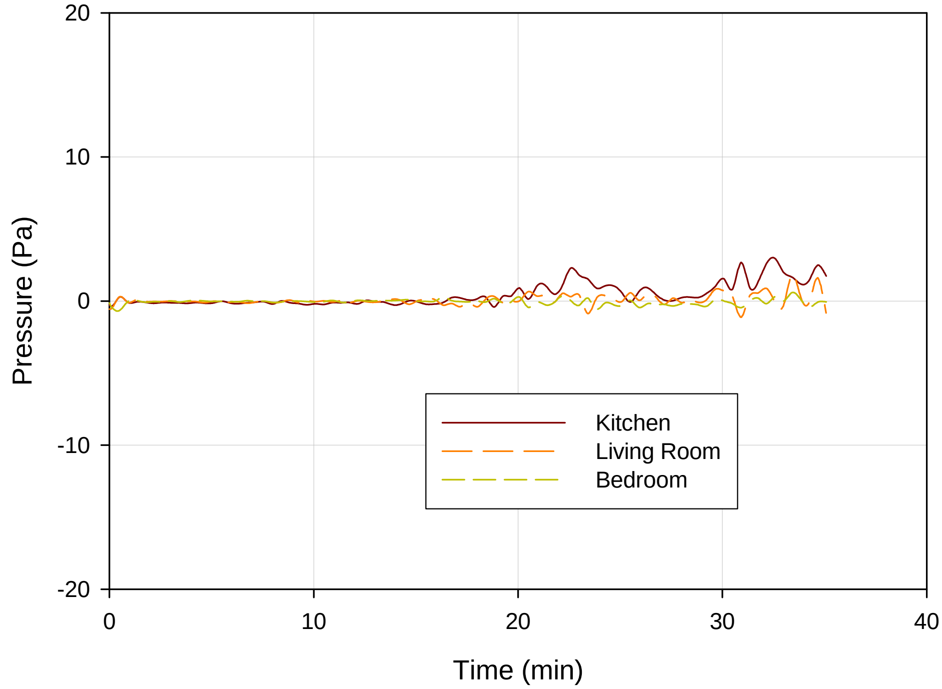

Figure E-18. Test CH3 (high cabinets, window removed) pressure comparison at 1.52 m

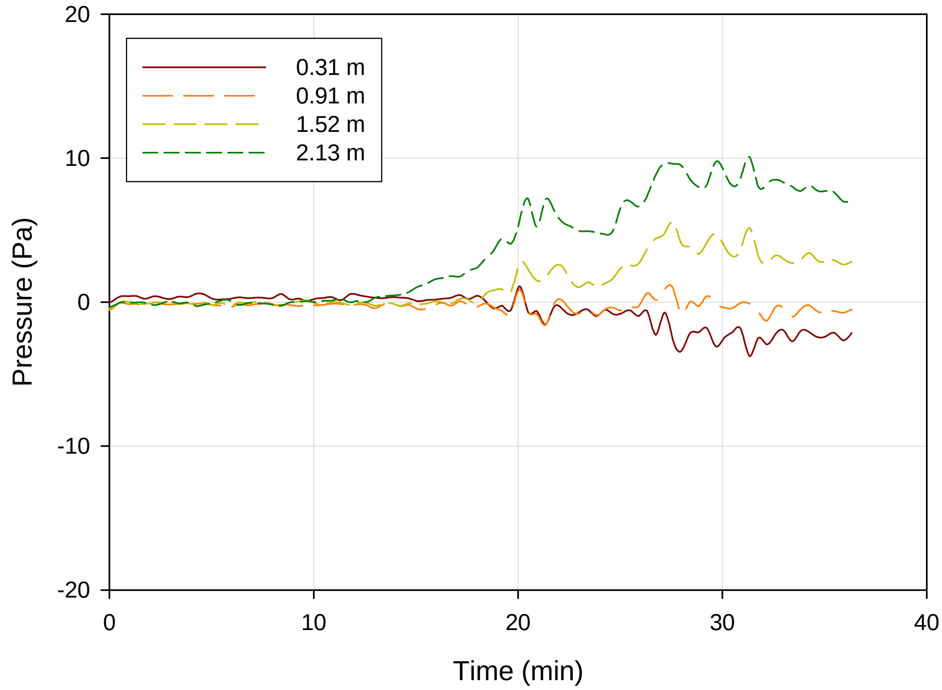

Figure E-19. Test CH4 (high cabinets, open door) pressures in room of origin (kitchen)

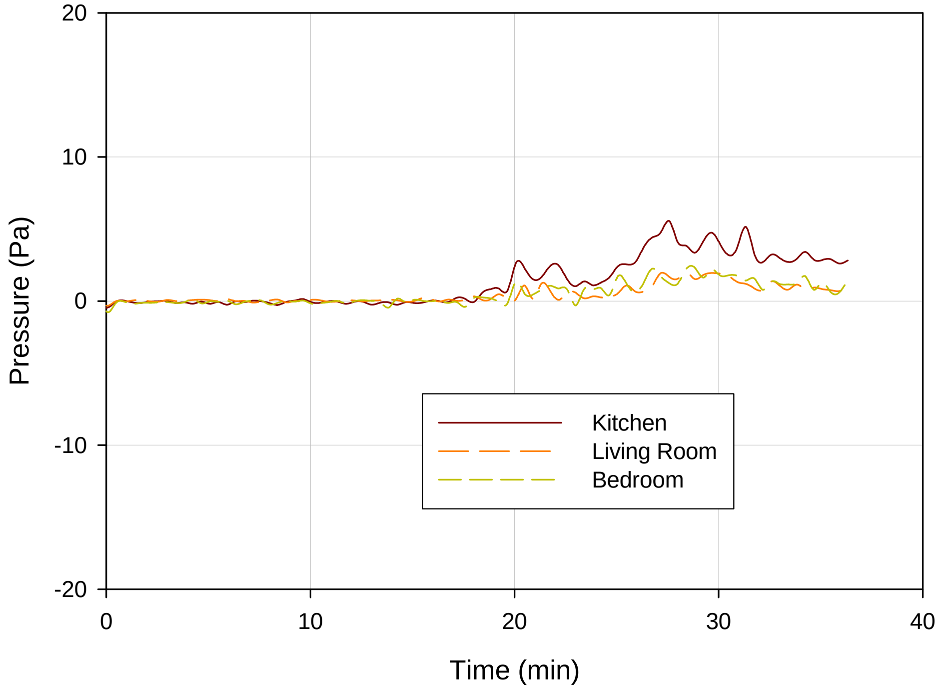

Figure E-20. Test CH4 (high cabinets, open door) pressure comparison at 1.52 m