ABSTRACT

Title of Thesis: THE ANALYSIS OF THE TRANSITION FROM SMOLDERING TO FLAMING IN POLYURETHANE CONTAINING ASSEMBLIES REPRESENTATIVE OF UPHOLSTERED FURNITURE

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The smoldering and ignition of upholstered furniture is the leading cause of loss of life in accidental residential fires. Due to these fatal incidents, a new smoldering apparatus experimental setup was designed and built to investigate the temperature profile, the gaseous products, and the probability of transition from smoldering-to-flaming in polyurethane foam based upholstered furniture when subjected to a high intensity cartridge heater representative of a cigarette. The measurement locations in which the gaseous products and the temperatures from smoldering combustion were determined ($2.5 - 22.5$ cm above the heater) and the materials that made up each upholstered furniture assembly (cotton and polyester fabrics and battings with both fire retardant or non-fire retardant polyurethane foams) were both varied during the tests to investigate the specific gaseous quantities compared with temperature readings as a smolder front propagates and how varying materials affect the transition from smoldering-to-flaming, respectively. On average, the rate in which the smolder front propagates near the end of the test is 2 times faster than the rate at the start of the test. All tests performed produced large amounts of Carbon Dioxide and Carbon Monoxide, which is representative of 95% of the Oxygen that was consumed. During the moments directly before the sample transitions from smoldering-to-flaming, there is a noticeable increase in Oxygen consumption as the distance from the heater increases past the smolder front and into the Oxygen limited pyrolysis zone. The anaerobic pyrolysis zone produces

the combustible fuels required for transition, and once a substantial amount of combustible fuel is produced, the high temperature smoldering reaction ignites the fuel. In varying the materials used in each upholstered assembly, it was confirmed that the probability of transition increased substantially with the use of cotton fabric and cotton batting, while the use of polyester fabric and polyester batting greatly reduced the probability of transition. The presence of fire retardants in fabrics and polyurethane foam can greatly reduce (or even eliminate) the probability of transition, but when paired with cotton batting, higher levels of fire retardants (BS 5852 rated) were required.

THE ANALYSIS OF THE TRANSITION FROM SMOLDERING TO FLAMING IN POLYURETHANE CONTAINING ASSEMBLIES REPRESENTATIVE OF UPHOLSTERED FURNITURE

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LIST OF ABBREVIATIONS

ASTM: American Society for Testing and Materials

BS: British Standard

Cot: Cotton

Cot-Poly: Cotton-Polyester Blend

DTA: Differential Thermal Analysis

FMVSS: Federal Motor Vehicle Safety Standards

FR: Fire Retardant

ICL: Israeli Chemical Limited

NFR: Non-Fire Retardant

NIST: National Institute of Standards and Technology

Poly: Polyester

PU: Polyurethane

SCFM: Standard Cubic Feet Per Minute

SRM: Standard Reference Material

TC: Thermocouple

TCPP: Tris(Chloropropyl) Phosphate

UFAC: Upholstered Furniture Action Council

%vol: Percent Volume

wt%: Percent Weight

1 INTRODUCTION

1.1 Background

The smoldering and ignition of upholstered furniture is the leading cause of loss of life in accidental residential fires. One of every 6.6 fires was started by smoking materials with upholstered furniture,[4] and although several tests, like ASTM E 1353,[1] NFPA260,[5] NFPA 261,[6] or California Technical Bulletin 113,[7] were developed to analyze upholstered furniture under smoldering conditions, none were created to determine the probability that these items would transition from smoldering-to-flaming.[3]

In 2010 to 2014, an average of 5,630 home structure fires per year were responded to by fire departments in which the first item to ignite was a piece of upholstered furniture. One of every thirteen of these fires had resulted in fatality.[4] Although fires starting with upholstered furniture only accounted for 2% of the reported home fires during this period, it accounted for 18% of home fire deaths.[4] Fires involving upholstered furniture can be severe because they can play two roles in the event. Upholstered furniture can be the first item that is ignited, and once the item is on fire, it creates a large heat release rate, causing the fire to spread easily; or it can contribute to an already growing fire and increase its growth substantially.[4]

Smoking materials (cigarettes, cigars, pipes, etc.) as the point of origin in which a fire started accounted for 27% of upholstered furniture based home fires.[4] In these types of fires, there was an annual average of "220 (50%) civilian deaths, 240 (35%) civilian injuries, and $73 million (27%) in direct property damage."[4]

This is not to say that the frequency of upholstered furniture based fires has not decreased. Since 1980, the amount of upholstered furniture fires have fallen by 85% from 36,900 fires to 5,400 fires.[4] Smoking materials being the cause of upholstered furniture fires has dropped from 62% to 27% because the Upholstered Furniture Action Council (UFAC) developed

flammability standards to prevent cigarette ignitions of a product, and the amount of adults smokers in the United States dropped from one in every 3 adults to one in every 5 adults.[4] However, the amount of fires caused by upholstered furniture, and those started by a smoking material, have plateaued; and it does not appear that this amount is decreasing by much anymore.

When smoking materials were the point of origin for a fire, the smoking materials usually initiate the process by causing an item of furniture to smolder. This smoldering furniture often transitions to flaming, and the subsequent fire is what causes fatal incidents. To combat these unfortunate occurrences, more research must be done on the analysis of the transition from smoldering-to-flaming so that actions can be taken to reduce the amount of upholstered furniture based fires caused by smoking materials.

1.2 Literature Review

Smoldering is considered a self-sustained, heterogeneous, combustion reaction which, especially in the case studied in this report, takes place within porous combustible materials.[8,9] Smoldering tends to start out as a weak reaction with a small amount of heat released, but as the reaction progresses, it produces enough heat within the reaction zone for the reaction to continue at a steady rate.[8,10] It is important for fire safety to be cognisant of smoldering fires because the combustion products can be toxic (causing people to lose consciousness and inhibiting people's respiration), and it can lead to the transition from smoldering-to-flaming that will quickly engulf the material on fire.[8–11] Smoldering is frequently an Oxygen limited reaction, so the amount of oxidizer in the reaction zone is a controlling factor that limits the overall reaction rate, the amount of fuel reacted, and the heat release rate.[8] This balance between the heat release rate at the reaction and the rate of heat transfer from the reaction determines the rate of smolder propagation.[8]

It should be noted that while there are multiple studies on the smoldering of different porous combustibles,[12–15] the focus of this review is on the smoldering-to-flaming transition.

The phenomena of a transition from smoldering-to-flaming is a complex process where the smoldering reaction provides both the heat that causes the pyrolysis of the virgin fuel and the heat source that ignites the resulting flammable gaseous mixture.[10] Many studies have been preformed trying to more thoroughly understand how this process works. The orientation of the sample has been shifted to observe the differences between vertical samples versus horizontal samples. The size of samples have been adjusted to observe if the amount of the sample effects the transition.[8–11] Different materials have been tested, but the main fuels used to analyze this transition from smoldering-to-flaming in experiments are cellulosic materials and polyurethane foam because of their common use in everyday upholstered furniture.[10] Thermocouples have been placed within samples to record the temperature profiles to determine how the smoldering front propagates and what temperature based trends occur on and within the sample.[8,9] The gaseous products that are produced at the surface of the sample have been analyzed to determine gas concentrations during the reaction.[9] The airflow introduced into the system has been varied to observe how highly oxidized materials are effected.[11]

Within a porous medium (of polyurethane foam for this report), the transport of energy and species is accomplished by diffusion, convection, and radiation, but in most fire scenarios, natural convection is the main source of heat and mass transport through the interior of the material.[8,9] When the fuel is ignited at the bottom,[3,8,10,11,16] the reaction propagates upward with the buoyancy induced oxidizer flow, making the smolder a forward reaction type.[8] In these forward smolders, the oxidizer comes in contact with the reaction zone after passing through hot char, and the hot post-combustion gases flow through the virgin fuel past the reaction, preheating it. This in turn implies that increasing the rate of the oxidizer flow to the smolder reaction zone increases the Oxygen supply, enhances the reaction, and increases the fuel preheating ahead of the reaction.[8] As the smolder reaction accelerates (due to the preheating ahead of the smolder front) and the oxidation of the char increases substantially, the surface oxidation reaction (smoldering) can transition to a gas phase combustion reaction

(flaming).[8]

Torero and Fernandez-Pello studied the smolder velocity and the reaction temperature as a function of fuel height and distance from ignition source (located at the bottom of the sample). The igniter consisted of a Nichrome wire in between two porous ceramic honeycomb plates.[8] To obtain the rate of smolder propagation, sheathed Chromel-Alumel thermocouples were positioned in porous polyurethane foam along the centerline of the fuel.[8] The smolder velocity was calculated from the time of the smolder reaction zone arrival between two adjacent thermocouples and the distance between those thermocouples.[8] Torero and Fernandez-Pello used polyurethane foam samples with a 150 mm square cross section and varying lengths of 150 mm, 175 mm, 200 mm and 300 mm to determine how scale affected the foam smolder.[8] It was found that as the smolder reaction approached the thermocouple locations, heat transfer from this reaction to the virgin foam ahead caused the virgin foam temperature to increase until it reached a high enough value for the smolder reaction to propagate through the virgin foam, demonstrating the preheating concept previously mentioned. As the smolder reaction passed the thermocouple, the temperature began to level off because the smolder reaction at that location had been completed.[8]

In the preheated area ahead of the smoldering reaction, Torero and Fernandez-Pello observed the formation of an endothermic pyrolysis reaction. In this reaction zone it was observed that the Oxygen was forced to depletion by the post-combustion gases and char oxidation reactions, leading to the heating of the virgin foam in an Oxygen-starved environment, causing an endothermic pyrolysis zone ahead of the smoldering front. This phenomena was observed in their data by a small plateau in the thermocouple results at 300°C.[8] The idea that the Oxygen's depletion was a driving force was backed up by the simultaneous occurrence of the pyrolysis reaction and the vigorous char oxidation.[8] Transition from smoldering-to-flaming appeared to occur when the char oxidation reaction was vigorous and after the reaction began to extinguish due to lack of Oxygen. During this time, the fuel continued to pyrolyze until the Oxygen replenished itself, the Oxygen mixed with the com-

bustible gases, and when a notable balance of fuel, Oxygen, and heat was reached, ignition occurs.[8,9]

Torero and Fernandez-Pello also observed a consistency in the propagation velocity between the smolder front and the pyrolysis front.[8] This propagation velocity appeared to have a strong increase from the start of the sample to the end of the sample with a consistent transition from smoldering-to-flaming for samples of 30 cm. This was a similar observation to other experimental findings where the transition from smoldering-to-flaming was very sensitive to the size of the sample (20 cm to 30 cm are prime sizes for transition).[9,10]

It was also observed that the igniter had no effect on the process after the first 5 cm of smolder propagation.[8] Chao and Wang verified this by comparing the power of the ignition source to that of the smoldering front. The thermocouples revealed that the heating rate of the foam from the second oxidation of char was about 10 times faster than that of the igniter.[9]

Chao and Wang conducted experiments on polyurethane foam that were horizontally oriented under natural convection with a focus on temperature, gas sampling, and thermal analysis to analyze the transition from smoldering-to-flaming.[9] They found that this orientation was important to consider because in a real life scenario, materials tend to burn in a horizontal configuration with air passing over the material instead of through it.[9] The foam's length, the ignition power, and the moisture content inside the foam were also analyzed when considering influences on how the sample transitioned from smoldering-to-flaming.[9] The ignition source for these experiments consisted of a ceramic plate wrapped by a Nichrome wire that was connected to an AC transformer that could be adjusted to investigate the effects of different igniter powers.[9] It was found that the initiation time for smoldering depended on the magnitude of this ignition power.[9] To analyze the gases that emitted from the sample, a flue gas analyzer was put above the top surface of the foam to measure the gas concentrations of Oxygen, Carbon Dioxide, and Carbon Monoxide.[9] The ignition power in these experiments varied from 40 W to 200 W.[9] The moisture content used by Chao and Wang's

samples varied from 0 to 4.3wt%.

It was observed that if transition from smoldering-to-flaming was to occur, it happened shortly after a vigorous second char oxidation past the smoldering front.[9] This second oxidation, based on Differential Thermal Analysis (DTA) results, was suggested to provide substantially more heat than the first oxidation, which would enhance the smoldering and improve the environment desired for a transition to flaming.[9] However, smoldering combustion is dependent on both the Oxygen supplied to the smolder reaction zone and the heat losses to the surroundings, so if the heat generated by this second char reaction was unable to overcome the amount of heat lost to the surroundings, the sample would eventually stop smoldering because there was not enough heat to support the reaction.[9]

Chao and Wang also found that the size of the foam played an important role in the sample's transition to flaming. If the foam length was longer, then larger heat losses from the exposed surface could be expected, naturally leading to a longer transition time.[9] Since it was also determined that a larger foam length increased the probability of a sample's transition to flaming, it makes sense that samples as long as 30 cm with increased moisture content could also transition to flaming. Samples of smaller sizes (with or without increased moisture content) were less likely to transition.[9]

Bar-Ilan et al. performed a study that observed the effect of flow velocity, Oxygen concentration, and thermal radiation on the transition from smoldering-to-flaming in small samples of polyurethane foam that were meant for spacecraft facilities (so microgravity was a factor).[11] Since the samples were of a far reduced size (5 x 5 x 10 cm^3) because of launch mass reasons for the International Space Station, smolder propagation had to be assisted by reducing the heat losses and by increasing the Oxygen concentration. The sample was vertically oriented with one surface open to an upward forced convective oxidizer flow parallel to the surface and a smolder ignition source (set to a power of 23.25 W) at the bottom of the sample (setup based on Tse et al).[11,17] Since the sample size was below the critical size for transition to flaming,[8] the heat losses were reduced by insulating the sample and increasing

its wall temperature; the heat generation produced by the smolder reaction was increased by increasing the Oxygen concentration of the oxidizer flow to make sure a sustained smolder was achieved.[11] To make sure the ignition source was not the cause of the transition to flaming, the ignition source was turned off once a sustained smolder reaction was achieved. The results of these assisted tests were consistent with what was previously found. Transition to flaming appeared to occur in the char region behind the smolder front. Bar-Ilan et al. also found that even with the small samples, a transition to flaming could be achieved by adjusting the Oxygen mole fraction and the forced flow velocities.

Putzeys et al. experimented on polyurethane foam and observed its transition from smoldering to flaming by using thermocouples and ultrasound probing.[16] They used the same experimental apparatus as Bar-Ilan et al.[11] The samples were 5 cm x 5 cm x 12.5 cm blocks of polyurethane foam that were oriented vertically, and they were subjected to a 23.25 W ceramic honeycomb igniter (to initiate the smoldering reaction), a 0.5 m/s forced flow, and an infrared radiant heater to counteract any convective heat losses.[16] Thermocouples were spaced evenly along the centerline of the sample to record the temperature progression throughout the test, and the ultrasound device used "speaker-microphone pairs to track the progress of the smolder reaction and to observe the evolution of the char."[16] With the ultrasound device, the permeability of the polyurethane foam could be determined. By conducting these experiments, large pores and high temperatures were found to occur in the char region preceding the smolder front. Putzeys et al. predicted that it was within the large pores that the transition to flaming occurred.[16] Before the transition to flaming, a secondary char oxidation occurred in this char region, which was theorized to generate the heat, the fuel, and the pores for a gas-phase ignition to occur.[16] They also found that increasing the Oxygen concentration or the radiant heat flux increased the creation of the pores that were inducive to the transition to flaming.[16]

Dodd et al. ventured into creating a numerical transport model that studied the transition from smoldering-to-flaming in polyurethane foam. In this model they were following the

theories and experimental setup used by Bar-Ilan et al.[11] and Putzeys et al.[16] This model was "two-dimensional with an eight-step reduced reaction mechanism" representative of a vertical 12.5 cm x 5 cm piece of polyurethane foam being subjected to a honeycomb igniter and a forced air-flow at the bottom of the sample to initiate the smolder.[10] During the simulation, the sample was also subject to a radiant heater to counteract heat losses from the sample, and either a forced or an opposed smoldering combustion could be simulated by their model.[10] Through the simulations that were performed it was determined that a two-temperature model was required to properly simulate the transition from smoldering-to-flaming because there were large temperature gradients between condensed phase and gas phase temperatures.[10] It was also observed that increasing the foam's porosity allowed Oxygen to mix with the gaseous fuel, which with the addition of heat caused the spontaneous combustion of the flammable gaseous mixture.[10] All eight of the reaction steps were required to accurately simulate the transition to flaming, and if any one of a specific four of the eight reactions were removed from the process, transition from smoldering-to-flaming would not occur at all.[10]

The current standard for evaluating cigarette ignition resistance for upholstered furniture materials is ASTM E 1353 (Figure 1a).[1] This standard evaluates the cigarette resistance of cover fabrics, interior fabrics, welt cords, filling/padding components, and other materials used in upholstered furniture.[1] With this information, an estimate on the performance of these materials when exposed to a smoldering cigarette can be determined.

Zammarano et al. redesigned ASTM E 1353 where buoyant air flow within the foam sample was enhanced to increase the smoldering magnitude by slightly modifying the sample holder. The sample holder was modified by introducing a wire mesh to support the foam and create a 13 mm gap between the foam and the sample holder. By inserting a gap between the foam and the sample holder, additional ventilation was encouraged. This sample holder was placed inside of an enclosure (Figure 1b). The ignition source for the polyurethane foam was a NIST Standard Reference Material (SRM) cigarette, and it was placed at the seam
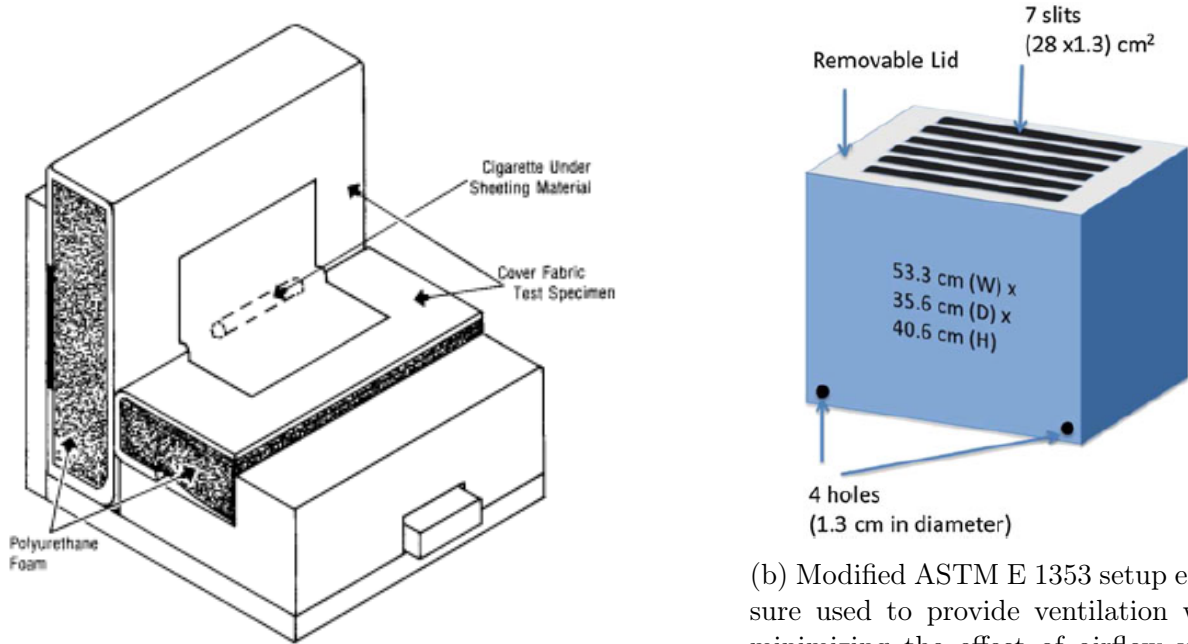
(a) ASTM E 1353 setup with a cigarette covered by a sheeting material being nestled in the crevice of two adjacent pieces of Polyurethane Foam.[1]

(b) Modified ASTM E 1353 setup enclosure used to provide ventilation while minimizing the effect of airflow variations over time in the hood and suppressing turbulence. The actual enclosure is transparent to easily view the ongoing experiments.[2]

Figure 1: Setup for ASTM E 1353 and modified enclosure used by Zammarano et al.[1,2]

in which the two foam blocks met, as presented by Figure 1a. With the exception of the foam blocks being supported by a steel wire mesh separated from the holder surface by 13 mm (to provide additional ventilation), all of the procedures described in ASTM E 1353 were followed.[3] For each of the tests using this setup, the polyurethane foam smoldered for an hour, 70% of the foam's mass was consumed, and no transition from smoldering-to-flaming was observed.[3] Most of the smoldering that occurred in this setup was focused in between the two adjacent polyurethane foam blocks directly beneath the SRM cigarette.[3] The surfaces of these foam blocks, that were initially pressed tightly together, began to open as the smoldering progressed, allowing a buoyancy driven airflow to flow through the opening.[3] Inside the opening, several portions of the foam's surface were noticed to glow red, indicating the high surface temperature and the high smoldering intensity.[3]

To reiterate, many studies have been performed to further understand the smoldering-to-flaming transition because upholstered furniture fires that have been initiated by smoking

materials (thus causing smoldering) are the leading cause of loss of life in accidental residential fires. Since a large amount of upholstered furniture items are polyurethane foam based, polyurethane foam was the main sample used in the studies reviewed above. Of the polyurethane foam samples that were tested, it was found that larger samples (20 cm - 30 cm) were more likely to transition to flaming. For samples that were smaller, increased heat and Oxygen concentration could be added to increase the likely hood that the foam would transition. When some sort of heater/ignition source started the smoldering process of the foam, the power of the heater was usually not a driving source of the reaction once the smolder had propagated far enough away from it. As the smolder front propagates, eventually the smolder front will produce enough heat to preheat the virgin foam ahead of the front. This preheated area is where pyrolysis occurs and combustible gaseous fuels are produced. In the char region, it was found that a secondary char oxidation occurs that provides high temperatures and large pores for a transition to occur. Computational modelling is still in the process of being created, but as the understanding of the transition from smoldering to flaming furthers, better models will be developed. There are several studies that were not reviewed for this report because they were more focused on just smoldering or flaming instead of the transition between the two.[14,15,18]

1.3   Goal and Objective

Although many worthwhile steps have been made in researching the transition from smoldering-to-flaming in polyurethane foam assemblies, more research is always required to develop a more comprehensive understanding of the process. Previous studies have not focused on quantifying the gaseous emissions of polyurethane foam with relation to the propagation of a smolder front as a transition from smoldering-to-flaming is approached. Not even a standard experimental setup has been developed to determine the probability that polyurethane foam based upholstered furniture would transition from smoldering-to-flaming. A key purpose of this study was to develop an experimental setup that would focus

on this probability to transition in a way that was repeatable. The apparatus in which these experiments were performed was designed to allow buoyancy induced airflow to move across the sample within a small gap while being subjected to a heater representative of a cigarette. These conditions were provided to replicate conditions encountered in crevices between real furniture cushions, where high intensity smoldering is known to occur,[2,18] that could produce a transition from smoldering-to-flaming. These tests were performed on both standard polyurethane foam assemblies and on more realistic assemblies that use mixtures of cotton, polyester, non-fire retardant polyurethane foam, and fire retardant polyurethane foam. This setup was also modified to simultaneously measure the temperature of the gaseous emissions coming off of the polyurethane foam sample and to quantify the percent volume of Oxygen, Carbon Dioxide, and Carbon Monoxide present along the path of propagation of the smoldering sample. These measurements were performed to gain more insight into the smoldering-to-flaming transition process.

2 EXPERIMENTAL SETUP AND PROCEDURES

2.1 Smoldering Apparatus

In the research that was performed for this study, two types of experiments were conducted. One type of experiment that was conducted focused on the physics of the transition from smoldering-to-flaming in a control-material setup (detailed description in Section 2.4). Another type of experiment that was conducted focused on the impact of various materials on the transition probability (detailed description in Section 2.5). Both of these types of experiments use the same smoldering apparatus (see Figure 2). This new smoldering apparatus focused on recreating a larger scale version of what happened in between the two foam blocks in the experiments of Zammarano et al.[2] The assumption being made here was that high smolder intensity is associated with a high probability of polyurethane foam transitioning from smoldering-to-flaming.[3] This apparatus design approximates smoldering conditions that may arise when smoking materials, like a cigarette, are placed in the crevices of an upholstered furniture item.[3]

The smoldering apparatus was designed to consist of two rectangular stainless steel, H-shaped channels whose housing was positioned on an aluminum frame with a sliding track as seen in Figure 2.[3] In Figure 2, the steel housing on the left is able to move along the sliding track, and the steel housing on the right is fixed in place and holding two pieces of 30 x 15 x 1.3 cm^3 ceramic fiber thermal insulation board. Protruding 4 cm from the bottom of the insulation boards is a 0.64 cm diameter high intensity cartridge heater, Comstat MCH1-38W-003, that is connected to a DC power supply. The purpose of the cartridge heater is to initiate the smoldering process by providing a well controlled source of ignition.[19] In preparation for experimentation, a sample was placed on the part of the housing that resides on top of the sliding track, the housing was moved along the track so that a small gap could be formed in between the sample and the opposing insulation boards, and the cartridge
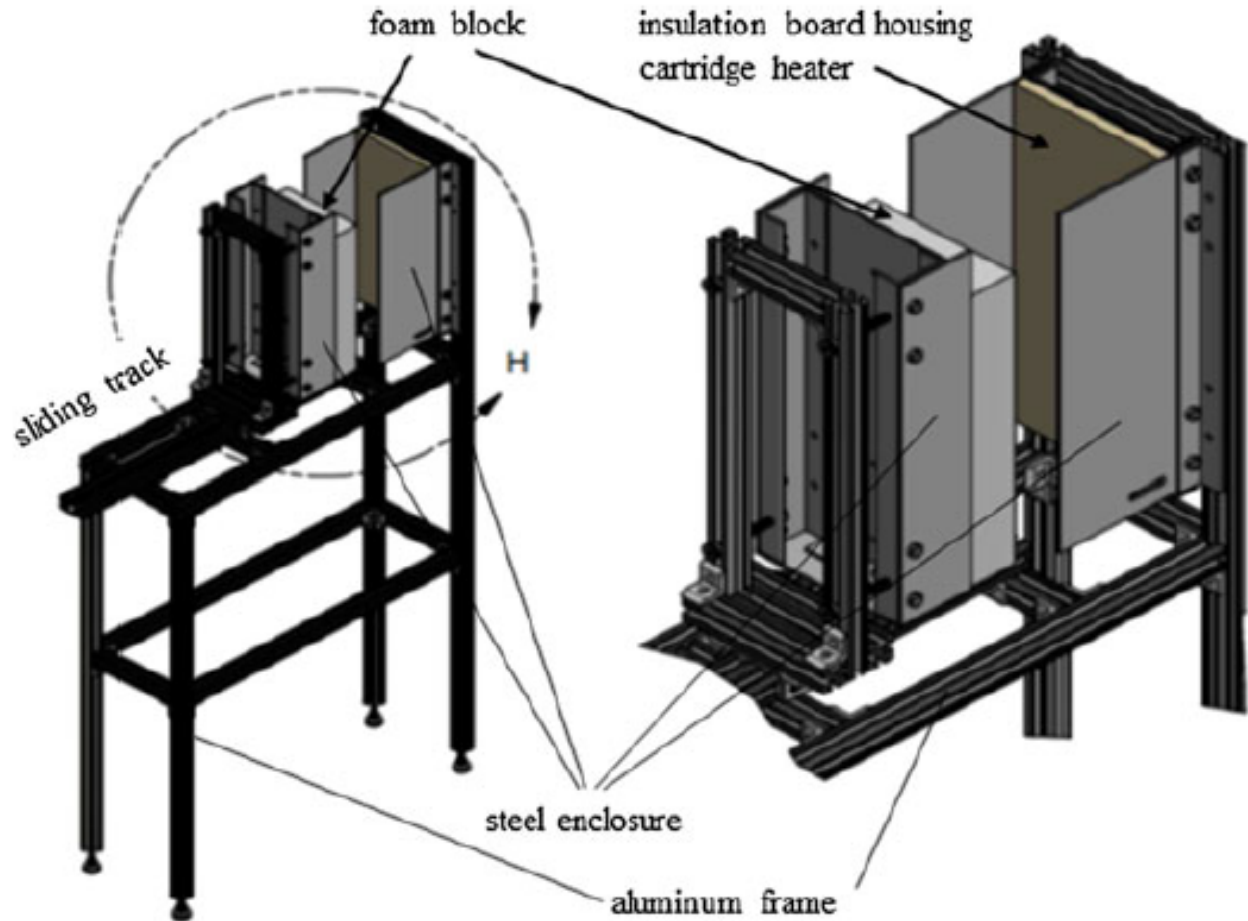
Figure 2: 3-Dimensional model of the smoldering apparatus.[3]

heater was pressed 1 *cm* into the sample. The aluminum frame and sliding track helped keep the sample in a vertical position and parallel to the opposing insulation boards.

The experiments that focused on the impact of various materials on the transition probability used a geometry similar to that shown in Figure 3. This figure gives a visual representation of what the sample setup for these types of experiments look like within the stainless steel housing of the smoldering apparatus. As shown, the sample, represented by a polyurethane foam block, is mounted on on a Ceramic Fiber Insulation Board. The sample creates a small gap with the opposing insulation board, and the cartridge heater is used to initiate the smolder process. With this repeatable setup, the probability that various materials will transition from flaming to smoldering can be observed.

(a) Side View   (b) 3-Dimensional View
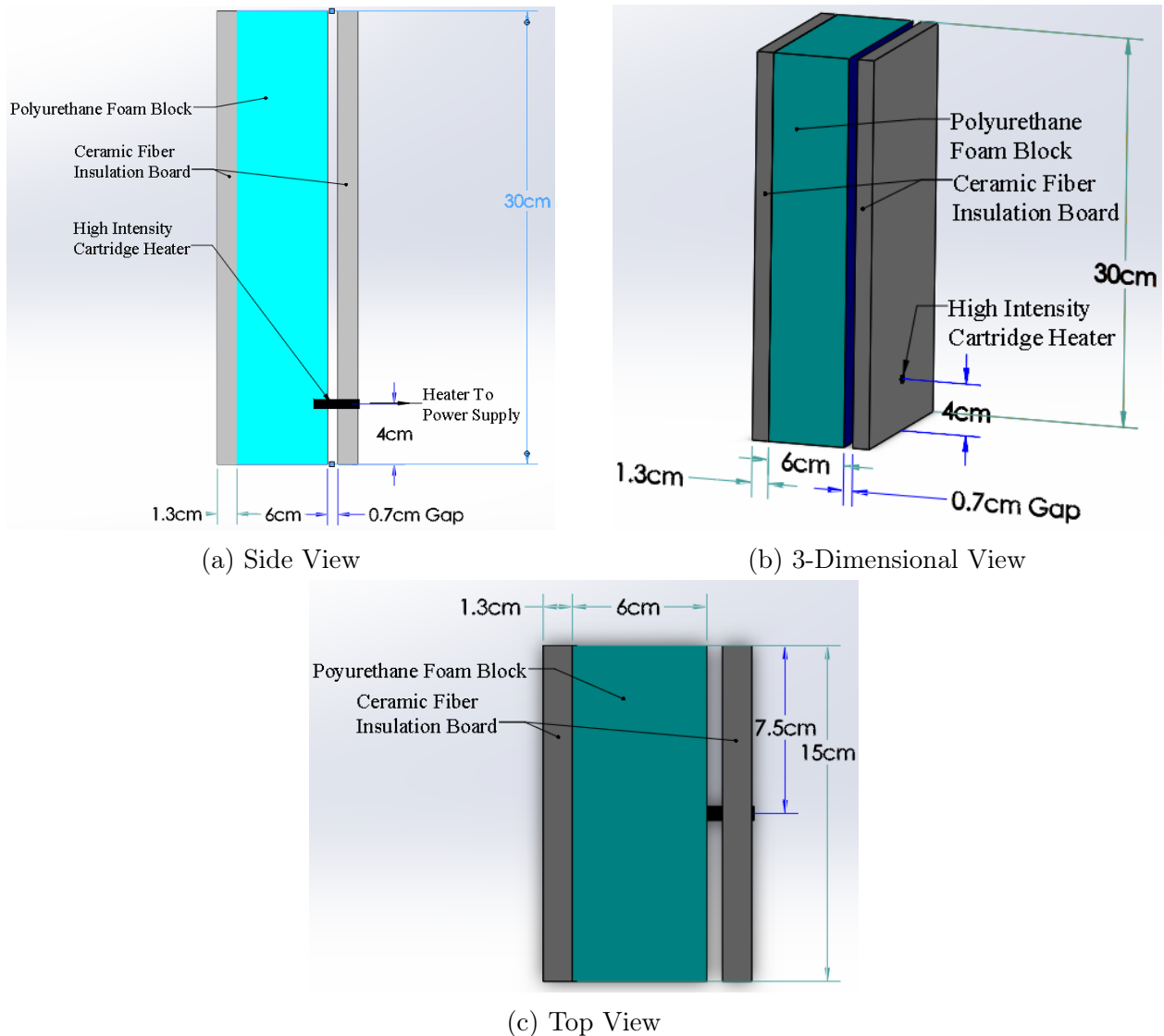
(c) Top View

Figure 3: The Fabric/Foam assembly geometry in position within the smoldering apparatus. (a) is a cross section of the side view. (b) is a 3-Dimensional view. (c) is a top view.

The types of experiments that focused on the physics of the transition from smoldering-to-flaming in a control-material setup used the geometry shown in Figure 4. This figure gives a visual representation of what the sample setup for these types of experiments look like within the stainless steel housing of the smoldering apparatus. Similar to the experiments that focus on the impact of various materials on the transition probability, these experiments also have a sample, represented by a polyurethane foam block, that is mounted on on a Ceramic Fiber Insulation Board. The sample creates a small gap with the opposing insulation board, and

the cartridge heater is used to initiate the smolder process in these experiments too. However, in this setup, a gas probe that collects the gases within the gap is added to determine the gas concentrations during the tests, and thermocouples are spaced vertically along the channel of the sample to determine a temperature profile during the test.
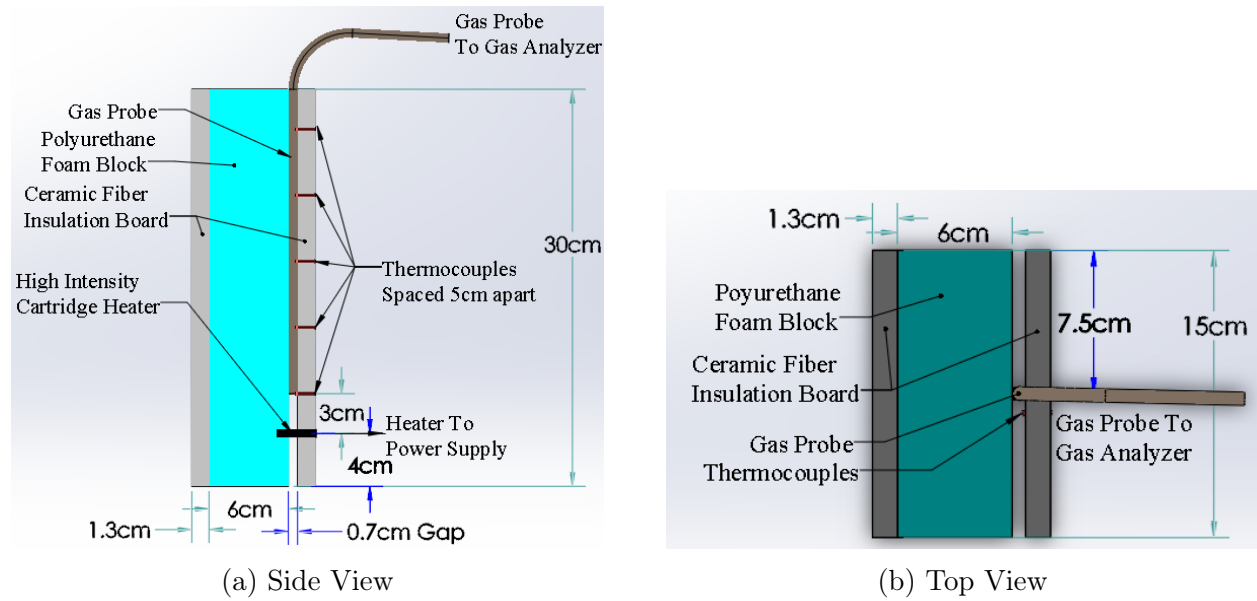
Figure 4: The Fabric/Foam assembly geometry in position within the smoldering apparatus with the addition of 5 thermocouples and a gas probe between the sample and the opposing insulation board. (a) is a cross section of the side view. (b) is a top view.

2.2 Materials: Foam, Batting, and Fabric

The following materials shown in Tables 1 and 2 were all of the materials that were used in the experimental portion of this study. All of the fabrics and battings, excluding fire retardant materials, were obtained from Test Fabrics,[20] a company that supplies textiles to laboratories for experimental and research purposes. The fire retardant materials were provided by Israeli Chemical Limited (ICL), and two different fire performance tests were performed to determine how the materials were rated, FMVSS 302 and BS 5852. FMVSS 302 (Federal Motor Vehicle Safety Standards 302)[21] is a standard that determines the burn resistance of materials within motor vehicles, but since it is used to classify fire performance of materials to reduce internal motor vehicle fires caused by matches and cigarettes, it was

Table 1: Outer Fabrics and Battings with their constituents, weight, and fire performance rating

Material	Constituents	Weight (g/m^2)	Fire Performance Rating	Notes
Cotton Fabric	100% Cotton	377	N/A	
Polyester Fabric	100% Polyester	210	N/A	
Cotton-Polyester Fabric	65% Polyester 35% Cotton	154	N/A	Poplin Mercerized and Bleached with an Optical Brightener.
FR Cotton-Polyester Fabric	<0.01wt% P <0.05wt% Cl 7.5wt% Br 5.5% Sb_2O_3	400	Passes BS 5852	Has 8.8wt% $C_{14}H_4Br_{10}$ Flame Retardant.
Denim Fabric	100% Cotton	393	N/A	Denim is used as a control material.
Cotton Batting	100% Cotton	658	N/A	It is 2.50 cm thick.
Polyester Batting	100% Polyester without resin	141	N/A	It is 1.25 cm thick.

deemed a satisfactory fire performance rating for the purposes of this study. BS 5852 (British Standard 5852) is standard that assesses the ignitability of materials used in upholstered seating by way of smoldering or flaming ignition sources, so materials with a BS 5852 rating were also deemed satisfactory to use in this study. The BS 5852 fabric and foam were flame retarded to ignition source 1 and to ignition source 5 respectively.[22]

For every test, using any setup that will be discussed in the next sections, all foam, batting, and fabric was conditioned in the same way. Each material was conditioned in an enclosed 30.5 x 50.8 x 61.0 cm^3 tank with desiccants (Drierite) for at least 24 hours before experimentation. The desiccants kept the tank at about 20% humidity. Fresh desiccants were added as necessary (denoted by the color of the Drierite turning from blue to pink).

Table 2: Foams with their constituents, weight, and fire performance rating

Material	Constituents	Density (kg/m^3)	Fire Performance Rating	Notes
(Non-FR) Polyurethane Foam	$<$0.01wt% P $<$0.05wt% Cl $<$0.05wt% Br	30.4	Fails FMVSS 302	No Flame Retardant. Airflow through the foam is 0.7 scfm.
FR (FMVSS 302) Polyurethane Foam	0.47wt% P $<$0.05wt% Cl $<$0.05wt% Br	28.8	Passes FMVSS 302	5wt% Non-Halogen-Phosphorus-Based Flame Retardant. Airflow through the foam is 1.6 scfm.
FR (BS 5852) Polyurethane Foam	0.87wt% P $<$3wt% Cl $<$0.05wt% Br	22.4	Passes FMVSS 302 and BS 5852	9.2wt% TCPP Flame Retardant. Believed to contain melamine. Airflow through the foam is 0.7 scfm.

2.3   Sample Mounting

2.3.1   Fabric/Foam Assembly Sample Setup for Analyzing the Transition Process

The types of experiments that focused on the physics of the transition from smoldering-to-flaming use a control fabric/foam assembly of denim fabric and non-FR polyurethane foam for its samples. These fabric/foam assembly samples start with a 30 x 15 x 6 cm^3 block of non-FR polyurethane foam with a 15 x 30 cm^2 piece of blue, denim, cotton fabric. Four ⅝ in stainless wire nails are used to pin the four corners of the denim fabric into one of the 30 x 15 cm^2 faces of the polyurethane foam. Four more ⅝ in stainless wire nails were used to pin the four corners of the other 30 x 15 cm^2 face of the polyurethane foam to a 30 x 15 x 1.3 cm^3 ceramic fiber thermal insulation board (288 kg/m^3). An example of this mounted fabric/foam assembly can be seen in Figure 5.
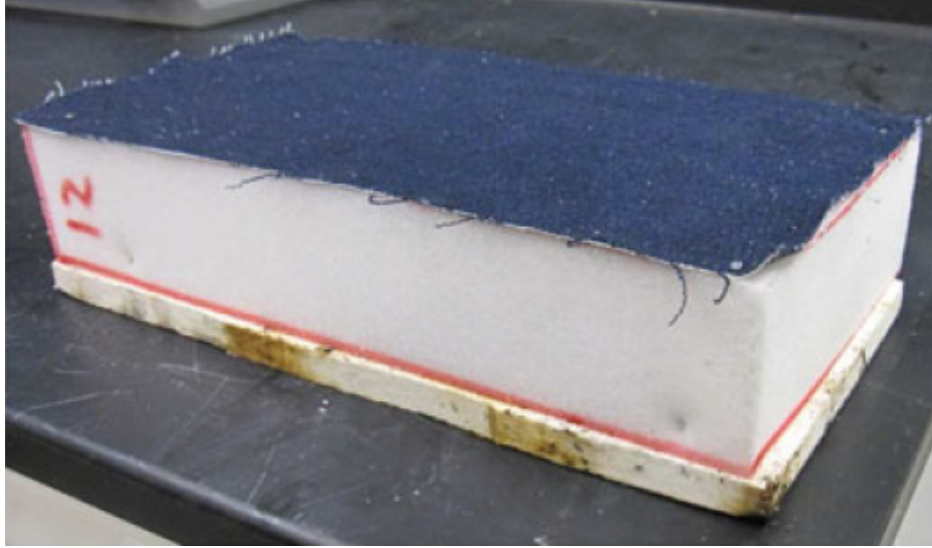
Figure 5: The setup of a fabric/foam sample, used for analyzing the transition process, mounted on thermal insulation board.[3]

2.3.2 Varying Fabric/Batting/Foam Assembly Sample Setup

The experiments that focused on the impact of various materials on the transition probability used the material combinations as specified in Table 3. The varying fabric/batting/foam assembly samples have several different materials that are placed together in a more realistic upholstery orientation, so the preparation of the sample is slightly different to the fabric/foam assembly used for analyzing the transition process.

Table 3: The Varying Fabric/Batting/Foam Assembly Samples. Each row describes what Outer Fabric, Batting, and Polyurethane Foam go into a particular sample

Outer Fabric	Batting	Foam
Cotton	Cotton	Non-FR Polyurethane
Cotton	Polyester	Non-FR Polyurethane
Polyester	Polyester	Non-FR Polyurethane
Cotton	Cotton	FR (FMVSS 302) Polyurethane
Cotton	Polyester	FR (FMVSS 302) Polyurethane
Polyester	Polyester	FR (FMVSS 302) Polyurethane
Cotton-Polyester	Cotton	Non-FR Polyurethane
Cotton-Polyester	Cotton	FR (FMVSS 302) Polyurethane
FR (BS 5852) Cotton-Polyester	Cotton	Non-FR Polyurethane
Cotton	Cotton	FR (BS 5852) Non-FR Polyurethane

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To prepare these types of samples, first a 30 x 15 cm^2 piece of batting is placed on one of the similar-sized sides of the polyurethane foam, and both are placed on a 42 x 27 cm^2 piece of fabric so that the batting is in between the foam and the fabric. The fabric is then wrapped up the longer sides of the foam and pinned at the corners using small ⅝ in stainless wire nails as seen in Figure 6a. The fabric was wrapped taut enough to eliminate any gaps in the assembly, but not too taut that the polyurethane foam was overly compressed. Then on the short sides of the assembly, the corners of the fabric were folded into itself, as seen in Figure 6b, and then folded up and pinned into place, as seen in Figure 6c. The face of the

(a) Step 1
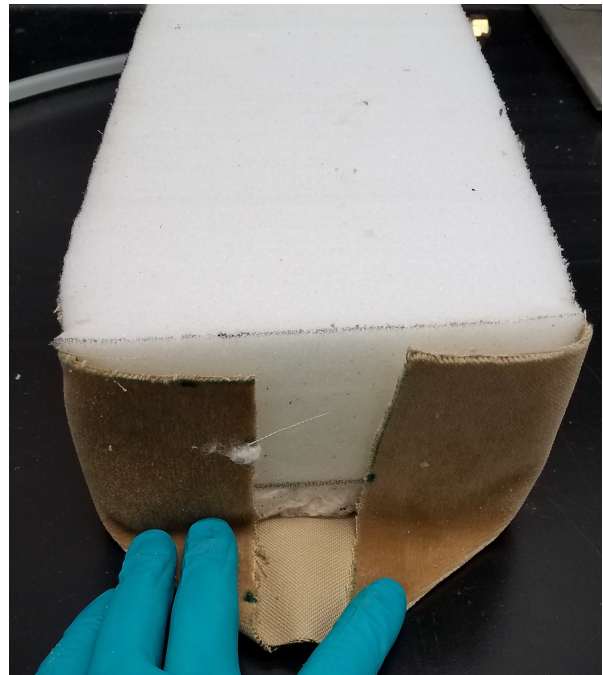
(b) Step 2

(c) Step 3

(d) Finished Sample Setup

Figure 6: The sample setup process for testing the propensity of varying materials to transition to flaming

assembly that still showed the foam was then pinned to a 30 x 15 x 1.3 cm^3 piece of ceramic fiber thermal insulation board at the corners, as seen in Figure 6d. More wire nails were added as required if the materials were not quite flush with the insulation board. This assembly was prepared like this to make a more realistic upholstery orientation.

2.4 Analysis-of-the-Transition-Process Procedure

The procedure for the experiments that focused on the physics of the transition from smoldering-to-flaming used a control fabric/foam assembly of denim fabric and non-FR polyurethane foam for its samples (Section 2.3.1). Before this control assembly was subjected to a test with thermocouples and a gas probe, it was configured as depicted in Figure 3 to determine its probability to transition from smoldering-to-flaming before adding tools to measure temperature and gas concentration.

In preparation for testing, the insulation side of the sample was placed against the sliding steel housing of the smoldering apparatus, and the steel housing was pushed inward until the space between the denim fabric and the insulation board opposite it was 0.7 cm ± 0.2 cm. According to preliminary testing, gap size had a strong influence on the probability that the sample would transition from smoldering-to-flaming, and a gap size of 0.7 cm ± 0.2 cm had a high probability to influence the transition from smoldering-to-flaming. The only portions of the gap that were open to the atmosphere were the top and the bottom. This small gap caused the cartridge heater to be pressed about 1 cm into the foam-fabric assembly. Once again, the cross section of this fabric/foam assembly that was used for analyzing the transition process can be seen in Figure 3a.

The smoldering apparatus was placed under a 500 kW exhaust hood in a position that would minimize the effects of the surrounding airflow while keeping the capability to evacuate any combustion products intact.[3] The airflow around the smoldering apparatus remained below 0.3 m/s, and the airflow inside the gap before the start of the test was a negligible airflow of less than 0.1 m/s.[3]

Before starting the test, the air temperature and the humidity of the testing facility was recorded, and the size of the gap in between the sample and the opposing thermal insulation board was double checked. Once everything was prepared correctly, a timer was started, the power source (connected to the high intensity cartridge heater) was turned on, and the power source was set to a power of 11 WDC, as this power is similar in magnitude to that of a smoldering cigarette.[3,9] Any interesting observations (first smoke wisps, color of the smoke, magnitude of the smoke, or the ignition) that were noticed during the experiment were qualitatively recorded with the time, and the experiment continued to run until the sample ignited or until 1 hour of time elapsed. The hood exhaust fan was turned on once the generated smoke began to leave the confines of the hood. If the sample transitioned to flaming, the sample was retracted on the sliding track, a portable Carbon Dioxide fire extinguisher was used to extinguish the fire, and the power source was turned off.

2.4.1 Data Collection of Temperature Measurements and Local Gas Percentage

The difference between the setup that analyzed the transition process and this setup was the addition of sources to measure the vertical temperature profile and the gases present within the gap of the apparatus, as seen in Figure 4. The way the temperature profile was acquired was by using OMEGA Precision Fine Wire Thermocouples with a diameter of 0.125 mm. Each thermocouple entered the apparatus through the steel on the back of the fixed housing and through both ceramic fiber thermal insulation boards like the cartridge heater, as seen in Figures 4a and 4b. The first thermocouple was 2.5 cm above the cartridge heater, and the remaining four thermocouples were distanced at 5 cm intervals directly above each other. All of the thermocouples were placed with a 1 cm offset to the left of the cartridge heater. The thermocouple beads were each barely within the gap between the sample and the insulation boards (no more than 2 mm). These thermocouples were all connected into a Fluke 2645A NetDAQ Data Acquisition Unit, which was connected to a computer where

the Fluke NetDAQ Logger software recorded the temperatures (°C) throughout the test.

To measure the gases present within the gap of the apparatus, a ZPA Infrared Gas Analyzer (Type: ZPA3) from California Analytical Instruments was used. To acquire the gases from within the apparatus, a vacuum pressure pump (made by Cole-Parmer) with a flow rate of 1.5 L/min sucked the gases from the tube in the apparatus (see Figures 4a and 4b) to the gas analyzer. The tube within the gap between the sample and the insulation board in the apparatus was a small copper tube with an outer diameter of 6.35 mm and an inner diameter of 4.83 mm. Thus, an estimate of the bulk velocity within the tube was 34 mm/s. This copper tube went out the top of the smoldering apparatus and made its way to a United Filtration 316L SS/Glass Filter housing with a coalescing cartridge that removed 99.5% of 0.01 micron liquids/solids inside it. This was an important step because all moisture and large particulates needed to be removed from the gas before entering the gas analyzer. The gas then went through the vacuum pressure pump, through two tubes filled with desiccant (Drierite) to remove any remaining moisture, and into the gas analyzer to be analyzed. The gases that were being measured throughout the duration of the test were Carbon Dioxide, Carbon Monoxide, and Oxygen. The volumetric percentages of these gases were sent from the gas analyzer, to a Fluke 2645A NetDAQ Data Acquisition Unit, and then to a computer where the Fluke NetDAQ Logger software recorded these values throughout the test.

The copper tube that leads from in between the gap of the smoldering apparatus was clamped onto one of the smoldering apparatus's vertical bars of 80/20 so that the tube was capable of being moved. By loosening/tightening the clamp, the tube could be shifted up and down to measure the gases at different elevations within the gap for each test. The elevations of the gas probe's orifice within the gap is level with the thermocouple placements (2.5. 7.5, 12.5, 17.5, and 22.5 cm above the heater). This does mean that while every test records the temperature data at each position, to measure the gas concentrations at multiple locations, a different test must be conducted for each individual location.

The Drierite and the coalescing filters were replaced as needed. If the Drierite turned pink, it was replaced with fresh blue Drierite before the start of the test. If the inside of the coalescing filter had turned a blackish-green, then it was replaced with a fresh white coalescing filter before the start of a test.

After the temperature and the humidity within the testing facility was recorded, after the fabric/foam assembly used for analyzing the transition process was placed within the apparatus with a 0.7 $cm \pm 0.2\ cm$ gap, and after everything else was prepared correctly, the test could begin. To start the test, a stopwatch and the Fluke NetDAQ Logger (software connected to the Fluke 2645A NetDAQ Data Acquisition Unit) were started at the same time. 30 seconds after the data had started recording, the power source connected to the high intensity cartridge heater was turned on and adjusted to 11 WDC. The test was observed for 1 hour or until the sample transitioned from smoldering-to-flaming. Anything notable that occurred (first wisps of smoke observed, color change in the smoke, increased intensity of smoke production, or transition to flaming) was recorded with the time in which the event happened.

Once the sample had ignited, instead of retracting the sample on the sliding track and extinguishing the flame, the sample was left within the apparatus until it had completely burned away. The reason for not extinguishing the fire was so the gas analyzer had time to acquire all of the data, and since the thermocouples were so small, this was also a precautionary measure to make sure the thermocouples did not break in the process. After the sample had extinguished on its own, the Fluke NetDAQ Logger was stopped. This test was repeated until a transition from smoldering-to-flaming was observed at least once for each gas probe location (2.5, 7.5, 12.5, 17.5, and 22.5 cm above the cartridge heater).

To gather the data required for this modified setup (Figures 4a and 4b), one of the most important parts was the ZPA Infrared Gas Analyzer (Type: ZPA3). For the gas analyzer to supply any meaningful data, it needed to be calibrated to read the correct values of Oxygen, Carbon Monoxide, and Carbon Dioxide when the gases were provided. To do this, the first

thing that needed to be established was a baseline value for each of the gases. A good way to establish this baseline value was to connect a canister of Nitrogen gas into the system. For convenience sake, the Nitrogen canister was connected into the vacuum pressure pump (replacing the tube that fed into the smoldering apparatus) for this calibration. The Nitrogen canister was opened (making sure the pressure started at 0 kPa) and the pressure on the gas regulator was adjusted to release Nitrogen at a pressure no higher than 3 kPa. This precaution was to make sure the tubes containing the Drierite were not over pressurized as doing so could cause the tubes to burst, spilling the Drierite.

As the Nitrogen went through the gas analyzer, the readings on its interface dropped substantially until the a steady value was reached. The Nitrogen was allowed to flow for another couple of minutes to make sure the reading was constant. After a couple minutes, the gas analyzer's interface was used to set the values that were being received for each of the gases to 0%vol because there was no Carbon Dioxide, Carbon Monoxide, or Oxygen in the Nitrogen canister. It should be noted that while these gases were being set to 0%vol, the ranges in which the gas analyzer read each gas were displayed. For the experiments in this report, Carbon Dioxide had a range of 0 - 10.95%vol, Carbon Monoxide had a range of 0 - 1.10%vol, and Oxygen had a range of 0 - 21.00%vol. Once the gases were zeroed, the Fluke NetDAQ Logger was started, and the voltages that the gas analyzer were sending the Fluke 2645A NetDAQ Data Aquistion unit were recorded with the Fluke NetDAQ Logger for 90 seconds. An average voltage was acquired for each of the gases over the 90 seconds.

The Nitrogen was then turned off and the tube that fed from the Nitrogen to the pump was replaced with a tube connecting the pump to a canister of compressed N.O.S. (Nitrous Oxide) that contained 8.238%vol of Carbon Dioxide, 0.8291%vol of Carbon Monoxide, and a balance of Nitrogen. The N.O.S was turned on and adjusted to 3 kPa. Once the readings for the Carbon Dioxide and the Carbon Monoxide had been steady for a couple minutes, the gas analyzer interface was used to set the Span of the gas for Carbon Dioxide and Carbon Monoxide to 8.238 and 0.8291 respectively. Then the Fluke NetDAQ Logger was started, and

the voltages that the gas analyzer were sending the Fluke 2645A NetDAQ Data Aquistion unit were recorded with the Fluke NetDAQ Logger for 90 seconds. The average voltage was acquired for Carbon Dioxide and Carbon Monoxide over the 90 seconds.

The N.O.S. was then turned off and the tube that fed from the N.O.S. canister to the pump was replaced with the tube connecting the pump to the smoldering apparatus. This meant that when the pump was turned on, the gas that was going to the gas analyzer was ambient air through the gas probe. Once the readings for the Oxygen had been steady for a couple minutes, the gas analyzer's interface was used to set the Span of Oxygen to 20.95 because an assumption is being made that the ambient air had an Oxygen concentration of 20.95%vol. Then the Fluke NetDAQ Logger was started, and the voltages that the gas analyzer were sending the Fluke 2645A NetDAQ Data Aquistion unit were recorded with the Fluke NetDAQ Logger for 90 seconds. An average voltage was acquired for Oxygen over the 90 seconds.

The average voltages were each plotted with its respective gas to create a line on a Gas Concentration (%vol) versus Voltage (V) plot. The trendlines that were obtained from these calibrations were used as equations within the Fluke NetDAQ Logger's software. The equations converted the voltages from the gas analyzer into gas concentrations in %vol, and thus meaningful data was produced.

Another task that was done to make sure the gas analyzer data was accurate was to determine the delay time and the response time. The delay time is the amount of time it takes the ZPA Gas Analyzer to react to gas being fed into it. This corresponds to the amount of time it takes for the gases within the gap of the smoldering apparatus to go into the gas probe, through all of the tubing, through the coalescing filter, through the pump, through the Drierite, and then make it to the actual gas analyzer. The response time is the amount of time it takes for the value shown by the gas analyzer to reach within 68% of the correct value.

To determine the delay time and the response time, the end of the gas probe was con-

nected to a supply of Nitrogen because it is known that the reading for Oxygen should be about 0%vol when subjected to only Nitrogen. The Fluke NetDAQ Logger was started with the gas analyzer just analyzing ambient air for 30 seconds. At 30 seconds, the gas probe was subjected to Nitrogen for 90 seconds, and then the Nitrogen was removed. The Fluke NetDAQ Logger was left recording for another 90 seconds before stopping it. This small test yielded a delay time of 15 seconds before the gas analyzer reacted and a response time of 15 seconds before the gas analyzer reached 68% of the correct value. Since the thermocouples were connected straight to the Fluke 2645A NetDAQ Data Aquistion unit, temperature readings collected from them were basically instantaneous. Thus, to make sure the gas concentration data is consistent with the temperature data, the first 30 seconds (15 seconds from the delay time and the response time each) of the gas concentration data was shifted back so the temperature reading at 1 second into a test corresponds with the gas concentration readings at 31 seconds into a test.

2.5 Procedure for the Testing of Propensity of Upholstered Furniture Materials to Transition

This varying fabric/batting/foam assembly procedure used the sample mounting described in Section 2.3.2, used a similar apparatus setup as seen in Figure 3, and had a very similar procedure to the analysis-of-the-transition-process procedure without the thermocouples or the gas probe. A sample was still placed on the sliding steel housing of the apparatus shown in Figure 2 with the insulation side of the setup against the steel housing. On the opposite side of the apparatus, there were still two pieces of 30 x 15 x 1.3 cm^3 ceramic fiber thermal insulation boards with a 0.64 cm diameter high intensity cartridge heater protruding 4 cm from the bottom of the insulation board. The difference between this varying fabric/batting/foam assembly setup and the general setup was that the outer fabric on these samples wrapped around the sides and pulled down the edges, so the thickness of the sample in the very middle was larger than the thickness at the edges. This variation in thickness

caused the gap in between the sample and the opposing insulation board to not be uniform. Thus, a new repeatable guideline was used for this setup where the gap size on the sides were 1.2 ± 0.6 cm, the gap size in the middle of the top was 1.0 ± 0.5 cm, the gap size in the middle of the bottom was 1.2 ± 0.6 cm, and the gap size at the thickest part of the sample was 0 cm. The reason that the gap dimensions at the middle were different for the top and the bottom of the sample was because the cartridge heater at the bottom pushes back at the sample, causing a greater variation in the gap dimension.

Other than these changes, the experiment was run in the exact same way as the general procedure. After the humidity and temperature of the testing facility was recorded, the stopwatch was started and the power source connected to high intensity cartridge heater was turned on and adjusted to 11 WDC. The experiment was observed until 1 hour had elapsed or the sample had transitioned to flaming. Any notable events that occurred during the test were recorded with the time. If the sample ignited, it was withdrawn on the sliding track, it was extinguished with a Carbon Dioxide fire extinguisher, and the power source was turned off.

3   RESULTS AND DISCUSSION

3.1   Analysis of the Transition Process

Thirteen tests were performed, using the analysis-of-the-transition-process procedure without the thermocouples or the gas probe, on four different types of polyurethane foam composites (52 tests),[3] but the only tests that will be mentioned in this report are those that used non-FR polyurethane foam and denim fabric. The facility where these tests were performed was not climate controlled, so the air temperature and relative humidity varied between 8°C - 26°C and 20% - 59% respectively over the period of the experimental campaign.[3] These environmental conditions, however, did not appear to have an effect on the transition probability, and mildly increased humidity did not change the transition probability of samples as long as 30 cm.[9] Earlier tests did show that high humidity (greater than 80%) may have had a negative impact on the probability to transition, so testing on days with that high of a humidity was avoided.[3]

In every test that transitioned to flaming, several stages could be observed. The first stage was the appearance of small wisps of smoke (Figure 7a). Once the smoke appeared, it slowly began to produce more smoke throughout the test. Figure 7b shows the wisps getting slightly thicker before turning into a noticeable plume (Figure 7c). This plume intensity increased in Figure 7d, where the smoke began to become less white and take on a slightly yellowish tint. Smoke production intensity increased substantially in Figure 7e where the plume was so dense that it could not be seen through anymore. When the test reached this stage, if the sample was going to ignite, it would usually happen within the next few minutes. Figure 7f shows the transition to flaming. It should be noted that in a majority of these tests, liquid pyrolysis products would sometimes drip from the bottom of the smoldering apparatus in the later half of the tests. Once the sample ignited, these drops would frequently continue to fall while on fire from the bottom of the smoldering apparatus.
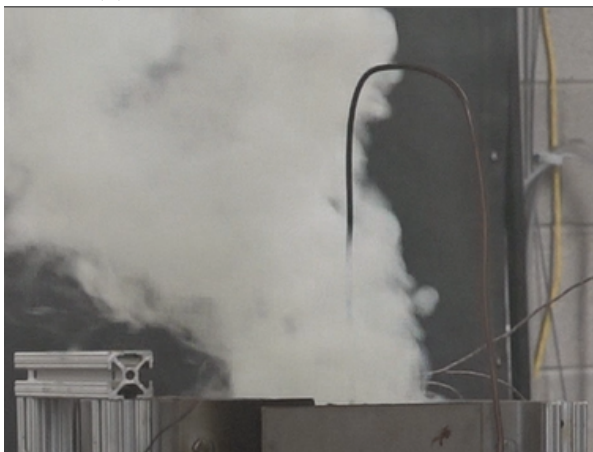
(a) First Wisps of Smoke

(b) Growing Wisps of Smoke

(c) Formation of a Smoke Plume

(d) Gradual Intensifying Smoke Plume

(e) High Density Smoke Plume

(f) Transition to Flaming

Figure 7: The stages of a non-FR polyurethane foam sample as it transitions from smoldering-to-flaming.

For the tests using this analysis-of-the-transition-process procedure and sample setup, it was found that 69% of non-FR polyurethane foam samples were able to transition. This probability is similar to the transition probability observed in full scale tests for a range of furniture items.[23] The time it took for the samples to transition from smoldering-to-flaming varied quite substantially (between 14 and 60 minutes).[3]

3.1.1 Results of Temperature Measurements

With the five evenly spread thermocouples along the vertical axis of the gap between the sample and the insulation, a reasonable temperature profile could be acquired for each test. An example of one of these temperature profiles can be seen in Figure 8, and there are a few things that should be noted. All of the thermocouples began to react to the temperature at staggering times with respect to the distance from the heater, which makes sense because the reaction was spreading vertically, so as the reaction zone moved upward, the thermocouples would react correspondingly.

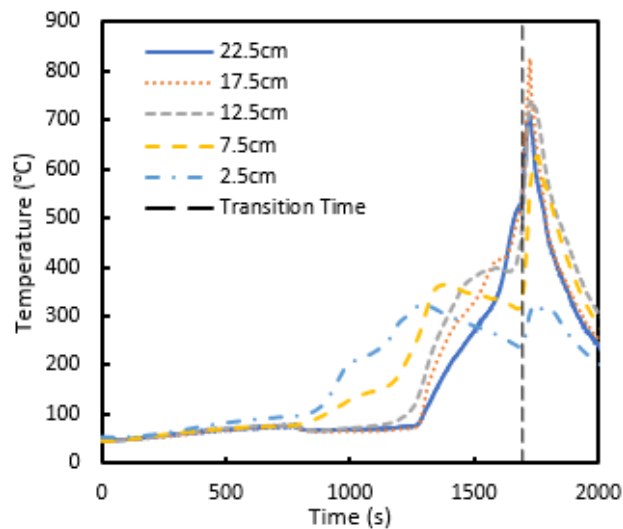Figure 8: The temperature profile within the gap of the smoldering apparatus while testing polyurethane foam with blue, cotton, denim fabric. Each curve depicts the temperature at a thermocouple's respective distance from the cartridge heater. The transition time marks the point in which the sample transitioned from smoldering-to-flaming. This figure only presents the data of one test that was performed.

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For the thermocouple curves at the distances of 2.5 cm and 7.5 cm above the heater, the temperatures reached a peak (first the thermocouple at 2.5 cm from the heater and then the thermocouple at 7.5 cm), and then the temperature curves decreased as they approached the transition time. Similar to the previous two thermocouples, the temperature curve for the thermocouple at 12.5 cm above the heater increased to a peak and then decreased slightly, but the magnitude in which it decreased was not nearly as substantial. The thermocouples at the distances of 17.5 cm and 22.5 cm did not peak before transition at all. This pattern can be explained by the passage of the smolder front. As the smolder front approached a particular thermocouple, the overall temperature increased. As the smolder front passed the thermocouple and began to gain distance from it, the temperature reading decreased because it was no longer in as direct of an exposure to the heat of the reaction. The reason the thermocouples at 12.5 cm, 17.5 cm, and 22.5 cm did not show this decrease as much was because their locations were roughly where the smolder reaction zone reached when the sample transitioned from smoldering-to-flaming.

3.1.2   Rate of Propagation for the Smolder Reaction Zone

The temperature profile can also be used to determine the rate of propagation of the smoldering reaction. If it is assumed that the temperature in which polyurethane foam reaches a high smoldering rate is 294°C, based on the TGA peak weight loss results in air from Shang,[24] then the times in which each thermocouple reached 294°C can be found, and the rate of propagation can be calculated. These rates of propagation were calculated by dividing the distance between two adjacent thermocouples by the difference in the time in which it took the adjacent thermocouples to reach 294°C each respectively.

Since each of these experiments' duration differ, the rates of propagation are not going to be exactly the same, but if the rates of propagation at each thermocouple location are averaged between each test, then a positive trend can be obtained. In Figure 9, the average rate of propagation has a positive trend, so as the reaction zone propagated up the sample,

31
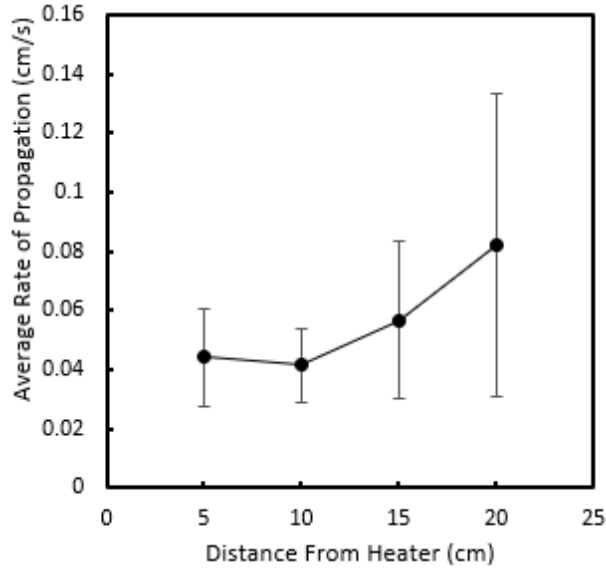
Figure 9: The average rate of propagation of the smoldering reaction versus the vertical distance from the heater. This data is representative of temperature readings from all five thermocouples in all of the tests that transitioned to flaming.

its rate increased as the distance from the heater increased. The average rate of propagation increased by almost two times by the end of the sample. The error bars in Figure 9 appear to be particularly large because they were calculated by determining the 95% margin of error between each of the experiments for each location, and since each of these experiments differed so much in duration, the error bars reflect this difference in time. However, based on the average rates of propagation at each location of the heater, a positive acceleration of the smoldering reaction was observed.

3.1.3 Temperature and Oxygen Analysis

The temperature can also be compared to the volumetric percentage of Oxygen that was extracted by the gas probe at the five locations vertically up the gap in the smoldering apparatus (2.5 cm, 7.5 cm, 12.5 cm, 17.5 cm, and 22.5 cm from the heater), as seen in Figure 10. In Figure 10, the Oxygen concentration data from five different tests, each with the gas probe located at a different elevation, were plotted with the thermocouple data that corresponded to the same test and gas probe elevation. It should be noted that for the

32
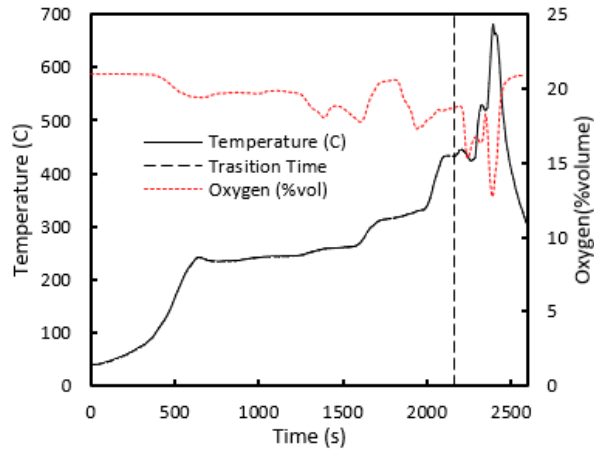
(a) 2.5 *cm* above heater
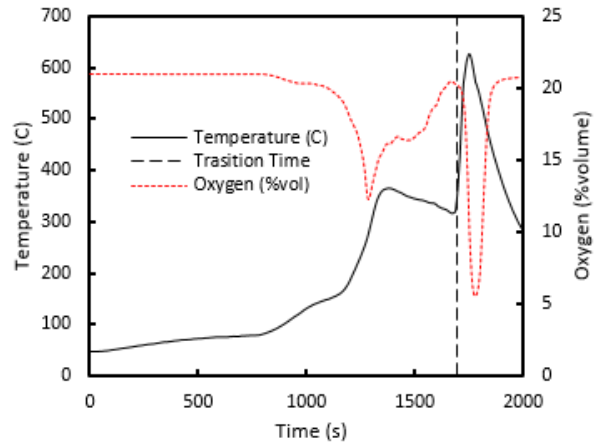
(b) 7.5 *cm* above heater
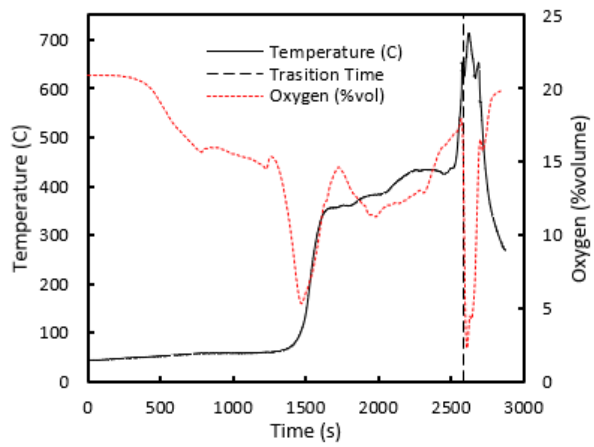
(c) 12.5 *cm* above heater
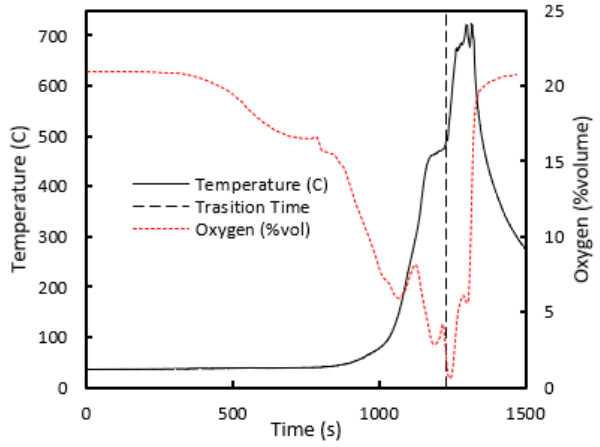
(d) 17.5 *cm* above heater
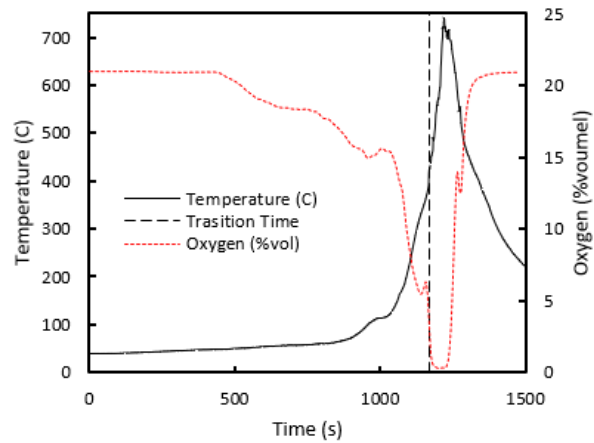
(e) 22.5 *cm* above heater

Figure 10: These graphs compare the volumetric Oxygen percentage versus time curves and the temperature versus time curves. The graphs show the data of the temperature and the volumetric Oxygen percentage at different location vertically within the gap of the smoldering apparatus. (a) is 2.5 *cm* above the heater, (b) is 7.5 *cm* above the heater, (c) is 12.5 *cm* above the heater, (d) is 17.5 *cm* above the heater, and (e) is 22.5 *cm* above the heater.

remainder of Section 3.1.3, it will be assumed that the locations 2.5 *cm*, 7.5 *cm*, 12.5 *cm*, 17.5 *cm*, and 22.5 *cm* refer to the distance above the heater.

The temperature at 2.5 *cm* increased with time as the sample approached the time of transition to flaming (In Figure 10a). The volumetric Oxygen percentage decreased slightly at 2.5 *cm*. At a point, the temperature rapidly increased to around 250°C and plateaued slightly while the local Oxygen dropped to about 19.50%. The transition time for this test was 2130 seconds (35 minutes 30 seconds) after the cartridge heater was turned on.

In Figure 10b, both the temperature and the volumetric Oxygen percentage at 7.5 *cm* acted in a similar way to Figure 10a. However, for Figure 10b the temperature reached a higher first peak of about 350°C, and the local Oxygen dropped to about 12% before returning to a value close to 20% prior to transitioning. The transition time for this test was 1664 seconds (27 minutes 44 seconds) after the cartridge heater was turned on.

At 12.5 *cm* (Figure 10c), again, the temperature reached a point where it increased rapidly to a first peak of about 350°C. However, this time, right as the temperature began to increase, the volumetric Oxygen percentage at 12.5 *cm* decreased sharply to about 5% and then increased back to around 15% as it approached the transition time. The transition time for this test was 2550 seconds (42 minutes 30 seconds) after the cartridge heater was turned on.

At 17.5 *cm* (Figure 10d), the temperature reached an initial peak temperature of about 450°C. This peak was much closer to the transition time than any of the previous tests. For the local Oxygen, its value decreased to about 6% right as the temperature began to increase, the Oxygen started to increase slightly, and then the Oxygen dropped more as it approached the transition time. The transition time for this test was 1200 seconds (20 minutes).

At 22.5 *cm* (Figure 10e), neither the temperature nor the Oxygen percentage reached an initial peak before the transition to flaming. Instead they continued to increase and decrease respectively into the transition. The transition time for this test was 1140 seconds (19 minutes) after the cartridge heater was turned on.

A couple overall observations can be made about the plots in Figure 10. The first observation is that each plot has a point in time where the temperature increased as the Oxygen concentration decreased. This can be explained by the passage of the smoldering front. The Oxygen concentrations at the higher elevations of 17.5 cm and 22.5 cm never rose back up substantially because the smoldering front either never passed this location before transition or the smoldering front only just passed this location before transition to flaming. These plots also show that the smoldering front consumed a substantial amount of Oxygen and generated a large amount of heat. From this it can be hypothesized that it is the temperature that drives the acceleration of the smoldering front. This acceleration of the smoldering front also led to nearly complete consumption of Oxygen at higher elevations of the samples. The point in time when the Oxygen was almost fully depleted at the higher portion of the sample was right before the transition from smoldering-to-flaming occurred.

In the 20 seconds before the transition, the relationship between the temperatures and the Oxygen measurements can be further observed at each location along the polyurethane foam in Figure 11. Since each test was so variable, the temperatures right before the samples transitioned from smoldering-to-flaming were quite different, but for each test, the samples transitioned to flaming in a range between about 300°C and 600°C. The most noticeable occurrence in the temperature data in Figure 11 was the sharp increase in temperature at 12.5 cm, and then past this point there was a gradual decrease in temperature as the distance above the heater increased (shown at 17.5 cm and 22.5 cm). This can be associated with the passage of the smoldering front. The temperatures at 2.5 cm and 7.5 cm had lower temperatures because the smoldering front had already past these locations. The temperature at 12.5 cm was the highest because this location was roughly where the smoldering reaction was occurring, and the smoldering reaction produces the most heat in this process. The temperatures past 12.5 cm decrease with distance because the thermocouples 17.5 cm and 22.5 cm were never exposed the direct heat of the smoldering reaction, but the heat of the smoldering reaction was still strong enough to preheat this area of higher elevations.
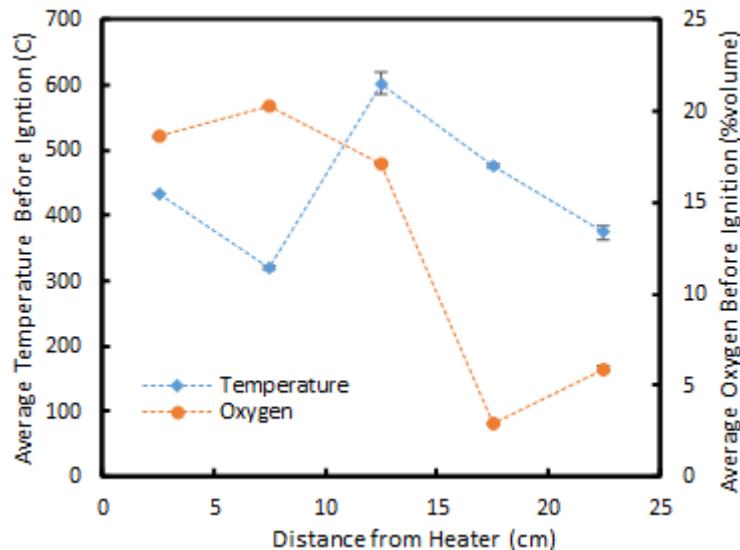
Figure 11: The average temperature and Oxygen measurements in the 20 seconds before ignition at 2.5 cm, 7.5 cm, 12.5 cm, 17.5 cm, and 22.5 cm above the heater. Most of the error bars are comparable to the size of the data points in this plot, thus hiding them from view.

Also observed in the 20 seconds before the transition from smoldering-to-flaming (Figure 11), there was a overall negative trend for the volumetric Oxygen percentage as the distance of the gas probe above the heater increased. The Oxygen Concentration at 2.5 cm, 7.5 cm, and 12.5 cm above the heater had a slight downward trend as the distance increased, but the Oxygen percentage for each location remained above 15%. This changed as the distance above the heater increased to 17.5 cm where the Oxygen percentage dropped to about 3%. At the distance of 22.5 cm, the Oxygen percentage increased to about 6%. This sharp decrease seen at 17.5 cm and 22.5 cm can be explained by the near complete consumption of the Oxygen by the smoldering reaction. Since the gap between the sample and the opposing insulation board was so small, very little Oxygen was able to enter the apparatus, so all of the Oxygen that does enter the apparatus was consumed by the smoldering reaction. This means the area past the smoldering front (around 17.5 cm and 22.5 cm) is where an anaerobic pyrolysis reaction occurs to produce the fuel required for transition from smoldering-to-flaming.

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In this section, a clear process of the transition from smoldering-to-flaming can be seen. As the temperature within the gap of the sample increases, the smoldering rate increases with it. The increase of the smoldering rate in turn further increases the temperature, preheating the virgin foam ahead of the smoldering reaction. Since the Oxygen supply is limited by the narrow gap, the smoldering reaction consumes all of the Oxygen, and the preheated foam past the smolder starts to pyrolyze instead of oxidizing. This anaerobic pyrolysis produces the fuel required for transition from smoldering-to-flaming, and once enough fuel is produced to overflow into the high temperature region of the smoldering reaction, sustained ignition occurs.

To further understand the physics of these transitions, a few more samples were tested with a gap size of 1.7 $cm \pm 0.2$ cm.[3] None of these tests transitioned to flaming even though it was observed that the smoke intensity was as high, if not higher, than previous tests with a smaller gap size.[3] Thus it is concluded that high smoldering intensity is necessary for transition from smoldering-to-flaming, but it is not sufficient enough to cause transition alone. When the gap between the sample and the insulation is small enough, the lower portion receives enough Oxygen to maintain a high temperature smoldering region, and the upper portion produces a substantial amount of gaseous fuel.[3] When the gap is increased, smoldering becomes the main process throughout the entire sample, and thus, not enough gaseous fuel is produced to yield a transition from smoldering-to-flaming.

3.1.4   Carbon Dioxide and Carbon Monoxide Analysis

In this section, the data for the Oxygen percentage was represented as a positive Oxygen consumption (%vol) caused by the smoldering reaction process. The Oxygen consumption and the Carbon Dioxide production from these tests were plotted together, as seen in Figure 12. It can be seen by each of the graphs in Figure 12 (5 tests each with different gas probe locations) that the Oxygen consumption curves and the Carbon Dioxide production curves had almost the exact same shape, but the Carbon Dioxide data had a smaller magnitude.
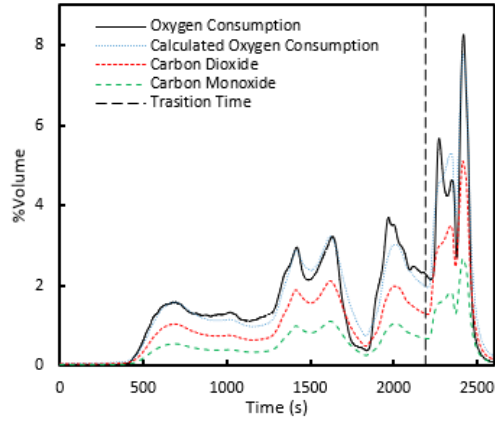
(a) 2.5 *cm* above the heater
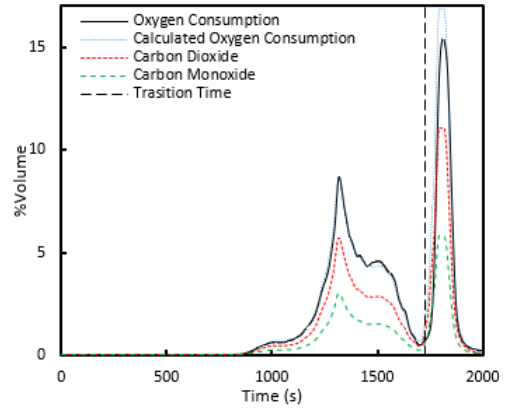
(b) 7.5 *cm* above the heater

(c) 12.5 *cm* above the heater

(d) 17.5 *cm* above the heater

(e) 22.5 *cm* above the heater

Figure 12: These graphs compare the Oxygen consumption, the Carbon Dioxide production, the estimated Carbon Monoxide production, and the calculated Oxygen consumption versus time curves at different location vertically along the centerline within the gap of the smoldering apparatus. (a) is 2.5 *cm* above the heater, (b) is 7.5 *cm* above the heater, (c) is 12.5 *cm* above the heater, (d) is 17.5 *cm* above the heater, and (e) is 22.5 *cm* above the heater.

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The only major difference that is noticeable between these Oxygen and Carbon Dioxide curves is that in Figure 12d, as the curves approach the transition time, the Carbon Dioxide reaches a plateau that is not representative of the experiment. It is not representative of the experiment because the range in which the gas analyzer was able to obtain values for Carbon Dioxide was not large enough to obtain the correct Carbon Dioxide percentages during this section of the test. That is why at about 1200 seconds (20 minutes) in Figure 12d, the Carbon Dioxide does not increase to a value more than 10.95%vol.

The Carbon Monoxide that was produced by these experiments was measured in the same fashion as the Oxygen and the Carbon Dioxide. However, similar to the Carbon Dioxide range problem mentioned about Figure 12d, Carbon Monoxide also shares a range problem, except on a much more substantial scale. The amount of Carbon Monoxide produced by these experiments far surpass the 1.10%vol maximum that the gas analyzer can read. This is understandable as smoldering produces substantially more Carbon Monoxide than flaming.[25] To rectify this issue and to obtain the Carbon Monoxide data, based on the comparison of valid Carbon Dioxide and Carbon Monoxide data, it is hypothesized that the ratio of the volumetric concentrations of Carbon Monoxide and Carbon Dioxide is constant. Thus, using the Carbon Dioxide and Carbon Monoxide data that did not surpass the ranges of the gas analyzer, ratios between the Carbon Monoxide and the Carbon Dioxide data at each probe location were found (Figure 13). The data seen in Figure 13 confirms that, after some induction period for each test, the ratio between Carbon Dioxide and Carbon Monoxide settle at a nearly constant value. These constant ratio values for each test were plotted against the distance from the heater as seen in Figure 13f. These ratio values from each test appear to have a somewhat positive trend, but considering the drop off in magnitude for the ratio at 22.5 cm above the heater, for the purposes of future calculations, it will be assumed that the average Carbon Monoxide and Carbon Dioxide ratio is 0.52 ± 0.08.

With this newly acquired ratio, a set of Carbon Monoxide production data was estimated, summed with the Carbon Dioxide production data, and compared with the Oxygen
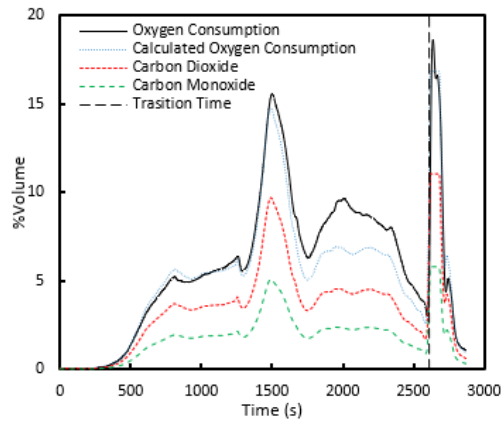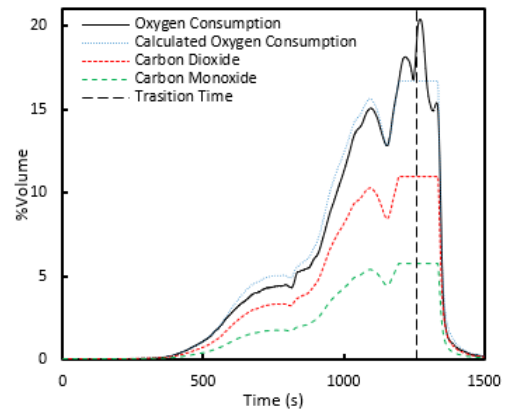
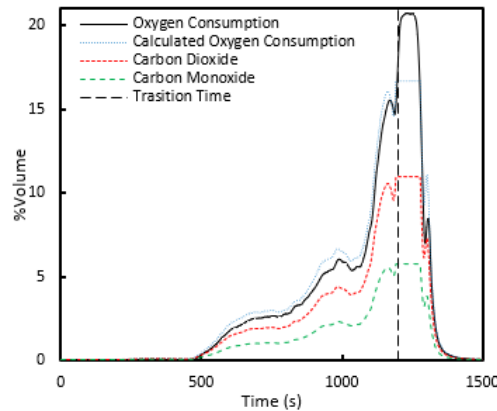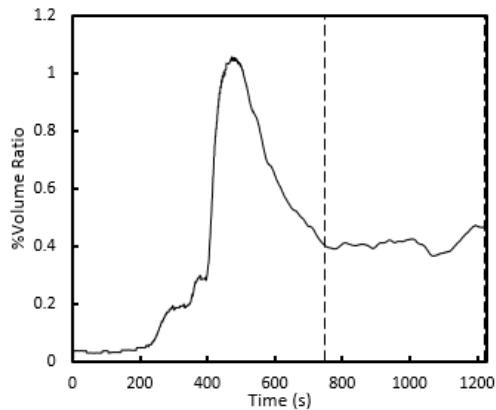(a) 2.5 *cm* above the heater

(b) 7.5 *cm* above the heater
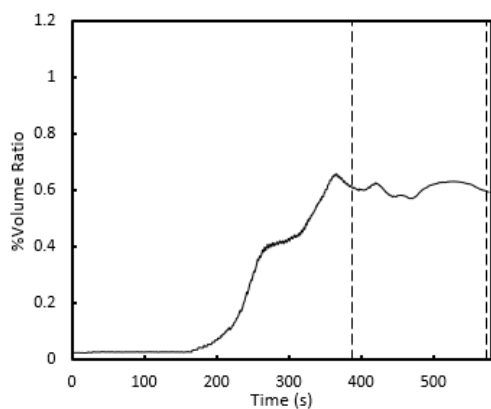
(c) 12.5 *cm* above the heater
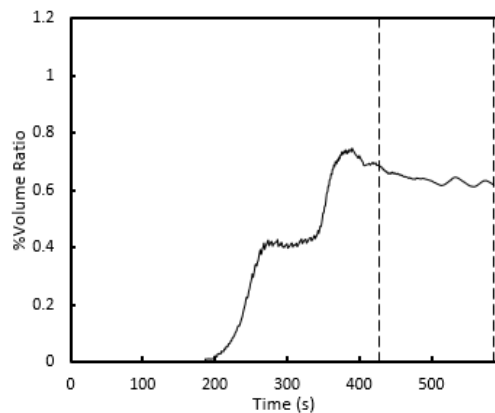
(d) 17.5 *cm* above the heater
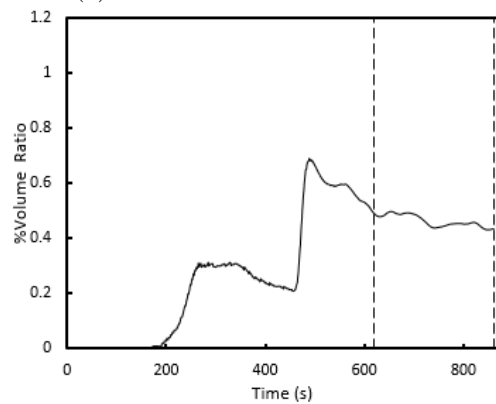
(e) 22.5 *cm* above the heater
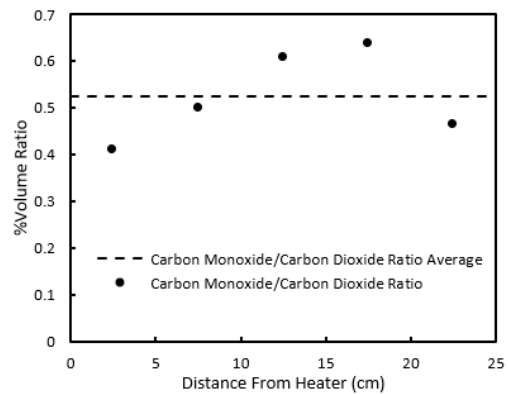
(f)

Figure 13: These graphs show the ratio of Carbon Monoxide and Carbon Dioxide versus time at (a) 2.5 *cm* above the heater, (b) 7.5 *cm* above the heater, (c) 12.5 *cm* above the heater, (d) is 17.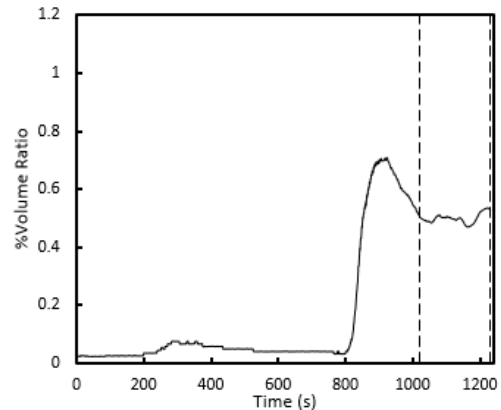5 *cm* above the heater, and (e) 22.5 *cm* above the heater. (f) shows the average ratio of the Carbon Monoxide and the Carbon Dioxide data for each location of (a)-(e), averaged between the two vertical bounds depicted in each graph. The error bars are comparable to the size of the data points in this plot, thus hiding them from view.

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consumption data (Figure 12). The purpose of this comparison was to determine how much of the Oxygen consumed by the reaction goes into producing Carbon Monoxide and Carbon Dioxide. This comparison yields that Carbon Monoxide and Carbon Dioxide production accounted for an average of 95% of the Oxygen the was consumed, and as seen in Figure 12, these calculated Oxygen consumption curves model the Oxygen data fairly well.

3.1.5   The Mechanism of Transition

From the previous sections (Sections 3.1.1 - 3.1.4), a mechanism for the smoldering-to-flaming transition can be determined. The process starts with the high intensity cartridge heater initiating the smolder reaction within the sample. As the heat generated by the smoldering reaction increases, the rate in which the smoldering reaction occurs increases too, thus further increasing the temperature in turn. This increasing temperature also preheats the foam past the smoldering reaction front. This concept can be seen in Figure 14.
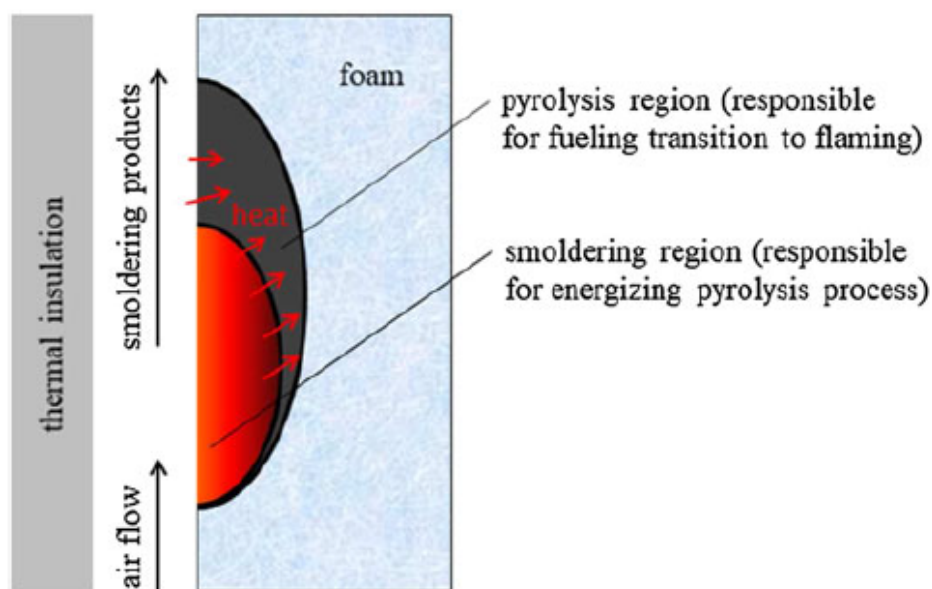
Figure 14: Physical view of how smoldering foam conditions lead to a transition to flaming combustion.[3]

As the smoldering reaction continues, progressively more Oxygen is consumed to produce mostly Carbon Dioxide and Carbon Monoxide, but these smolder reaction products are

unable to serve as combustible fuel to initiate the transition to flaming. However, since the Oxygen supply is limited by the narrow gap within the apparatus, the Oxygen approaches being almost completely consumed, and anaerobic pyrolysis begins in the preheated region above the smolder front. Pyrolysis becomes dominant in regions with little to no Oxygen, so the oxidizing smolder reaction needs to consume the majority of the Oxygen for the pyrolysis to occur. The pyrolysis reaction is what produces the fuels necessary for transition, so once enough pyrolysis products have been produced to overflow into the ever increasing temperature of the smoldering reaction region, the transition from smoldering-to-flaming occurs.

3.2 Propensity of Upholstered Furniture Materials to Transition

The following results describe how each material combination (described in Table 3) reacts when subjected to a heater within this smoldering apparatus using the procedure described in Section 2.5. A material combination's probability to transition to flaming and its probability to continue smoldering for the duration of the test are shown in Figure 15. It should be noted that the graph is organized with a clear trend showing which materials have higher probabilities for the transition from smoldering-to-flaming and continuous smoldering. The decreasing probabilities shown in Figure 15 show that assemblies with more cotton in them have a higher chance to transition from smoldering-to-flaming than assemblies with more polyester in them, and assemblies with fire retardant materials reduce the probability to transition if they contain a large amount of fire retardants and/or they are paired with a polyester material.

In Sections 3.2.1 - 3.2.10, observations of how each material combination reacted in the smoldering apparatus are organized by the types of materials that were used instead of the probabilities that the samples would transition to flaming or continue to smolder.
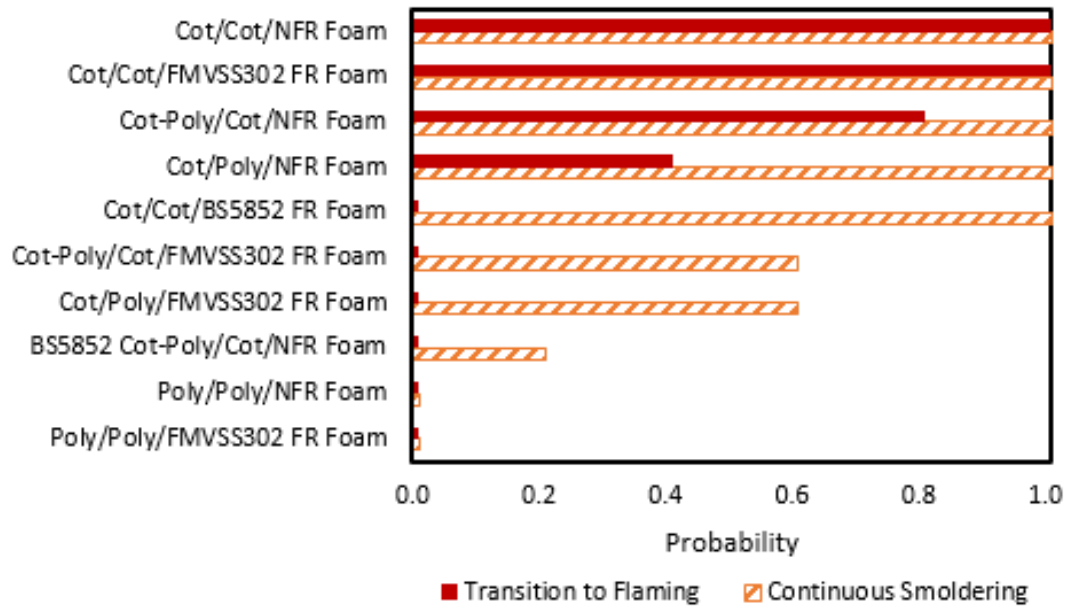
Figure 15: The probability of each material combination transitioning from smoldering-to-flaming alongside the probability that each material combination will smolder (with high intensity) continuously throughout the test. The graph is organized from highest to lowest flaming transition probability, and then it is organized from highest to lowest probability of continuous smoldering.

3.2.1 Cotton Fabric / Cotton Batting / Non-FR PU Foam

(Cot/Cot/NFR Foam):

Cotton has a high probability to cause the transition from smoldering-to-flaming. For each of the 5 tests performed with cotton fabric, cotton batting, and non-FR polyurethane foam, the sample always transitioned to flaming within 31 - 45 minutes of exposure to the heat source. The first wisps of smoke were always observed within 4 minutes of exposure to the heat source. This 100% chance to transition from smoldering-to-flaming indicates that when cotton materials are used with non-flame retardant foam, it will likely result in a fire when exposed to a heat source with a power similar to or greater than that of a cigarette.

3.2.2 Cotton Fabric / Polyester Batting / Non-FR PU Foam

(Cot/Poly/NFR Foam):

The presence of polyester batting with cotton fabric and non-FR foam changes how

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the sample transitions from smoldering-to-flaming even with a smoldering inclined material like cotton fabric as the first point of contact with the cartridge heater. As a thermoplastic, polyester batting tends to melt away from the heat source instead of propagating the smolder of the material to the rest of the sample. Of the 5 tests that were performed, only 2 samples transitioned to flaming, but of the samples that did not ignite, high intensity smoke production was still observed until an abrupt stop in smoke production was observed. The first wisps of smoke were always observed within 4 minutes of exposure to the heat source, and the samples that did transition to flaming had ignition times from 24 to 42 minutes. For the samples that did not transition to flaming, the fact that smoke just stopped being produced indicates that the polyester batting inhibits smolder.

3.2.3 Polyester Fabric / Polyester Batting / Non-FR PU Foam

(Poly/Poly/NFR Foam):

As previously mentioned, polyester is a thermoplastic which melts away from heat sources, and because of this behavior, 0 out of 5 of the samples that were tested with polyester fabric, polyester batting, and non-FR polyurethane foam were able to transition to flaming. The first wisps of smoke were delayed (4 - 10 minutes) compared to that of the tests that used cotton materials. The continued production of this smoke was very minimal throughout the entire test. Since the samples did not transition to flaming and they did not suffer much thermal degradation at all, it was possible to remove the sample from the apparatus for further analysis (Figure 16). By pulling back the layers of the polyester fabric, and then the polyester batting, it can be seen that the polyester melted back to form a defined air gap away from the heat source. The thermal degradation on the foam was only an indent that was about 1 *cm* deep. Although the polyester fabric, the polyester batting, and the non-FR polyurethane foam all showed signs of the thermal decomposition, it is clear to see in Figure 16 that a char is formed that prevented any further decomposition of the samples.

(a) Poly/Poly/NFR Foam
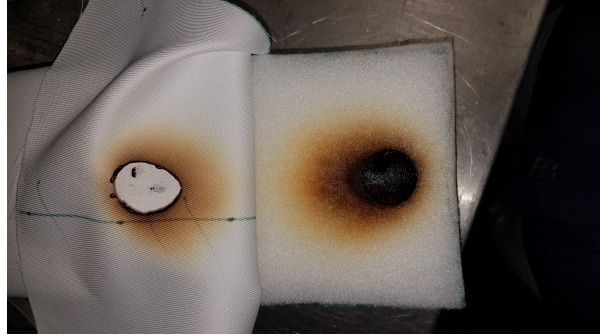
(b) Poly/Poly/NFR Foam showing the batting
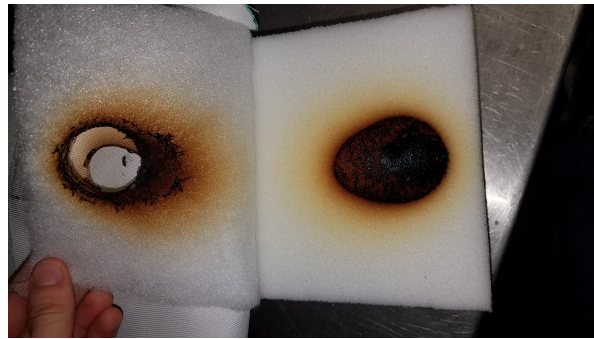
(c) Poly/Poly/NFR Foam showing the foam

Figure 16: Polyester Fabric/Polyester Batting/Non-FR Polyurethane Foam assembly after smoldering test was performed. (a) shows the plain sample after the test. (b) shows the sample with the polyester fabric lifted up, revealing the polyester batting. (c) shows the sample with the polyester fabric and batting lifted up, revealing the non-FR polyurethane foam.

3.2.4 Cotton Fabric / Cotton Batting / FR (FMVSS 302) PU Foam

(Cot/Cot/FMVSS302 FR Foam):

As discussed previously, sample combinations that use cotton fabric, cotton batting, and non-FR polyurethane foam always led to the transition from smolder to flaming. When the non-FR polyurethane foam was replaced with a FMVSS 302 rated FR polyurethane foam, the sample still ignited 5 out of 5 times. The time it took to observe the first wisps of smoke with the FMVSS 302 rated FR foam had a slightly larger spread (3 - 5 minutes), and the time it took for the samples to transition to flaming varied from 30 to 45 minutes (similar to the Cotton Fabric/Cotton Batting/Non-FR Foam), but overall the samples always ignited. This shows that the strong smoldering behavior in the cotton fabric and the cotton batting overwhelms the fire retardants that were present in this FMVSS 302 rated FR foam.

3.2.5 Cotton Fabric / Polyester Batting / FR (FMVSS 302) PU Foam (Cot/Poly/FMVSS302 FR Foam):

When using the FMVSS 302 rated FR polyurethane foam with the cotton fabric and polyester batting, 0 out of 5 of the tests performed were able to transition from smoldering-to-flaming, but 3 out of 5 tests still had high intensity smoke production. During the tests, the sample produced smoke consistently until 30 - 40 minutes of exposure to the heat source had elapsed. Interestingly enough, it appeared that when a couple samples were exposed to slightly higher levels of ambient humidity in the testing facility, very little smoke was released at all. While the FMVSS 302 rated FR polyurethane foam still transitioned to flaming when paired with the cotton fabric and cotton batting, it appears that the addition of the flame retardant was able to reduce the transition probability of the cotton fabric and the polyester batting to 0%.

3.2.6 Polyester Fabric / Polyester Batting / FR (FMVSS 302) PU Foam (Poly/Poly/FMVSS302 FR Foam):

The results from when the polyester fabric and the polyester batting were tested with the non-FR foam are very similar to when they were tested with FMVSS 302 rated FR polyurethane foam. Similar thermal damage was observed where the polyester fabric and batting melted away from the cartridge heater creating an air gap with a char ring surrounding it. It was observed that the indent that was made in the FMVSS 302 rated FR polyurethane foam was about 1 cm. None of the samples that were tested were able to transition from smolder to flaming and a substantial amount of smoke was never produced. It also appears that when the samples were subjected to much higher ambient humidity levels in the testing facility, the smoke ceased to be produced much quicker than when the ambient conditions had a much lower ambient humidity level.

3.2.7 Cotton-Polyester Fabric / Cotton Batting / Non-FR PU Foam (Cot-Poly/Cot/NFR Foam):

Cotton-Polyester blended fabrics are very common in furniture assemblies, and when this material alternative is used with cotton batting and non-FR polyurethane foam, the samples transitioned from smolder to flaming 4 out of 5 times, and high intensity smoke production was observed in 5 out of 5 tests. The smoke production was consistent in nature with the other tests that transitioned from smoldering-to-flaming and used cotton batting with non-FR polyurethane foam. The first wisps of smoke were observed at about 3 minutes, and the samples ignited between 39 and 49 minutes.

3.2.8 Cotton-Polyester Fabric / Cotton Batting / FR (FMVSS 302) PU Foam (Cot-Poly/Cot/FMVSS302 FR Foam):

Using FMVSS 302 rated FR polyurethane foam with cotton-polyester blended fabric and cotton batting yielded 0 out of 5 samples to transition from smoldering-to-flaming, but high intensity smoke production was observed 3 out of 5 times. The first wisps of smoke varied from 1 - 3 minutes, and the volume of smoke that was produced varied substantially between smoking a lot throughout the test to barely smoking at all. This suggests that this combination may require further research to determine why some of the samples smoked profusely while other samples did not.

3.2.9 FR (BS 5852) Cotton-Polyester / Cotton Batting / Non-FR PU Foam (BS5852 Cot-Poly/Cot/NFR Foam):

When using a BS 5852 rated FR cotton-polyester fabric with cotton batting and non-FR polyurethane foam, 0 out of the 5 samples transitioned to flaming, and high intensity smoke production was only observed 1 out of 5 times. The initial wisps of smoke were observed at about 2 minutes after being exposed to the heat source, but the rate in which the sample produced smoke stayed low and consistent throughout the duration of the 1 hour

tests. One of the samples continued to smoke after 1 hour had elapsed, and when the sample was removed from the apparatus, it began smoking profusely. However, the majority of the samples that used BS 5852 rated FR cotton-polyester fabric with cotton batting and non-FR polyurethane foam neither transitioned to flaming nor produced a large amount of smoke, suggesting that BS 5852 rated fabrics are fire retardant enough to withstand the high probability that cotton materials have to transition from smoldering-to-flaming.

3.2.10 Cotton Fabric / Cotton Batting / FR (BS 5852) PU Foam (Cot/Cot/BS5852 FR Foam):

While cotton fabric and cotton batting always ignited when paired with non-FR foam or FMVSS 302 rated FR foam, the presence of BS 5852 rated FR polyurethane foam yielded 0 out of 5 samples to transition from smoldering-to-flaming, but high intensity smoke production was observed 5 out of 5 times. This implies that there are at least enough fire retardants added to the BS 5852 rated FR polyurethane foam to go from a 100% transition probability with FMVSS 302 rated FR polyurethane foam to a 0% probability to transition from smoldering-to-flaming. However, the nature in which both fire retardant foams smoked were very similar in initial smoke observation time (about 3 minutes) and the total volume of smoke produced.

3.2.11 Propensity of Upholstered Furniture to Transition Conclusions

There was a clear pattern observed between the probability of transition from smoldering-to-flaming and the materials that were used in each fabric/batting/foam assembly. The assemblies that used cotton fabric with cotton batting had the highest probability to transition from smoldering to flaming as long as BS 5852 rated FR polyurethane foam was not used with them. The materials with the next highest probabilities to transition had non-FR polyurethane foam grouped with cotton-polyester fabric and cotton batting, then cotton fabric and polyester batting. This suggests that while polyester and polyester blends were able

to inhibit transition, it was not enough to completely stop the transition from smoldering-to-flaming while cotton materials and non-FR polyurethane foam were used. However, for every sample combination that had a non-zero probability to transition, continuous smoldering throughout the test duration was observed 100% of the time.

For the samples that did not transition to flaming, the assemblies that used cotton materials had the highest probability to smolder continuously. The assemblies that used cotton fabric with cotton batting had the highest probability to smolder continuously when grouped with BS 5852 rated FR polyurethane foam. This shows that BS 5852 rated FR polyurethane foam contains enough flame retardants to inhibit the high transition probability found in cotton materials, but the cotton materials are still able to smolder profusely for the duration of the tests. The materials with the next highest probabilities to have continuous smoldering for the duration of the tests have FMVSS 302 rated FR polyurethane foam grouped with cotton-polyester fabric and cotton batting, then cotton fabric and polyester batting. This suggests that the addition of FMVSS 302 rated FR polyurethane foam to cotton-polyester fabric/cotton batting and cotton fabric/polyester batting assemblies is enough to inhibit the assemblies from transitioning to flaming at all and reduce the probability that the samples smolder for the duration of the tests. The next material combination with highest probability to transition from smoldering to flaming uses BS 5852 rated FR cotton-polyester fabric, cotton batting, and non-FR polyurethane foam. This shows once again that BS 5852 rated materials are able to prevent the transition from smoldering to flaming, and by replacing cotton fabric with BS 5852 rated FR cotton-polyester fabric, the probability that the assembly will continue smoldering reduces substantially. The material combinations that cause a 0% probability to both transition to flaming and have continuous smoldering include polyester fabric and polyester batting. This makes sense because polyester is a thermoplastic which melts away from heat sources. This propensity to inhibit both the transition to flaming and smoldering at all is represented by a decrease in probability for each material combination with any polyester in it, including the blended materials.

4 CONCLUSIONS

A new experimental smoldering apparatus was developed to reliably analyze the temperature profile, the gaseous products, and the probability of transition from smoldering-to-flaming in polyurethane foam based upholstered furniture when subjected to a high intensity cartridge heater representative of a cigarette. The tests performed with this new apparatus utilized samples of a fabric/batting/foam assembly, and the key quantities being extracted from these tests were the gaseous concentrations, the temperature profile, and the probabilities that various materials would transition to flaming. Using these quantities, the physics of the transition from smoldering-to-flaming could be analyzed and the impact of various materials on the transition probability could be determined.

In analyzing the physics of the transition from smoldering-to-flaming, thermocouples were used to analyze the temperature profile of the samples. By finding when each thermocouple reached 294°C (the temperature in which polyurethane foam reached a high smoldering rate[24]), a rate of smolder propagation was found to have a strong positive trend. As the smolder front propagated up the sample, the rate in which it spread increased by almost two times. As the temperature increased, the intensity of the smoldering reaction increased, which in turn further increased the temperature of the smoldering region and increased the rate in which smoldering front propagated. This progressively increasing temperature was able to preheat the region of the virgin polyurethane foam ahead of the smoldering front too.

When the temperature was compared with the Oxygen concentration within the gap of the apparatus, a clear relationship could be seen. As the temperature increased as the smoldering reaction approached each thermocouple, the gas probe at each thermocouple location detected a decrease in Oxygen concentration. This suggests that smoldering reaction was, in fact, an Oxygen limiting reaction, and the cause for the propagation of the smoldering front was temperature dominant. Since there was little to no Oxygen present in the smoldering region as the smoldering front progressed, the preheated area ahead of the smoldering front

was able to pyrolyze and create gaseous combustible fuel in an Oxygen limited environment.

When compared, the Oxygen consumption (%vol) had an almost identical trend as Carbon Dioxide (%vol), except the Carbon Dioxide was of a lower magnitude. The amount of Carbon Monoxide (%vol) generated during these experiments was roughly half (0.52 ± 0.08) the amount of Carbon Dioxide generated. When the Carbon Dioxide and the Carbon Monoxide were summed together and compared to the Oxygen consumption, it was seen that about 95% of the Oxygen consumed went into producing Carbon Dioxide and Carbon Monoxide. Thus, while the smoldering reaction consumed the majority of the Oxygen within the gap of the apparatus, combustible fuels required for a transition to flaming were not produced by the smoldering reaction. Therefore, the transition from smoldering-to-flaming requires the combustible fuels produced by the anaerobic pyrolysis zone. To solidify this theory, tests were run with larger gap sizes (greater than $0.7 \; cm \pm 0.2 \; cm$) within the apparatus, and while continuous high intensity smoldering did occur, 0% of the samples transitioned from smoldering-to-flaming because not enough gaseous combustible fuel was produced.

To reiterate, for the transition from smoldering-to-flaming to occur, a temperature driven smoldering reaction is required to consume the majority of the Oxygen within the small gap of the smoldering apparatus. The smoldering reaction both preheats the virgin foam ahead of the smoldering front and provides an Oxygen limited region favorable of anaerobic pyrolysis. The pyrolysis produces the combustible fuels, and once there are enough combustible fuels to overflow into the high temperature region of the smoldering reaction, the sample transitions from smoldering-to-flaming.

Samples of multiple compositions representative of realistic upholstered furniture was also examined for continuous smoldering and transition to flaming propensity. The denim-polyurethane (non-FR) foam assemblies setup used for analyzing the physics of the transition from smoldering-to-flaming had a 69% probability to transition from smoldering-to-flaming. For samples with cotton fabric and cotton batting, the likelihood of transition to flaming is very high, even in the presence of lightly fire-retardant polyurethane foam (FMVSS 302 rated

polyurethane foam). Only highly flame retardant foam (BS 5852 rated foam) was capable of preventing the transition from smoldering-to-flaming in assemblies that used cotton fabric and cotton batting. Using polyester batting greatly reduces the probability of transition, and using polyester fabric with polyester batting prevent the transition from smoldering-to-flaming all together. Using the highly fire retardant materials that were BS 5852 rated prevented the transition to flaming, even when paired with cotton batting, the strongest smolder ignition source. This indicates that if a sufficient flame retardant is used, it will most likely always prevent the transition from smoldering-to-flaming. However, the presence of this flame retardant does not necessarily reduce the probability that high intensity smoke production will occur.

4.1 Future Work

Since the data collected suggest that this apparatus can determine the probability that a realistic representation of upholstered furniture will or will not transition from smoldering-to-flaming, future work on this subject is sure to occur. Many augmentations can be made to this experiment, like the analysis of airflow speed within the gap of the apparatus, more spatial temperature measurements along the foam surface, or the addition of more types gases for the gas analyzer to determine. With this repeatable design, much more research can be performed to even further understand the transition from smoldering-to-flaming.

Another possible outcome of this study is the eventual publication of a new ASTM standard for testing various material combinations when subjected to a cigarette-type ignition source. With a new standard in place, various types of materials can be analyzed, and the probability that these materials will transition to flaming will become known. With more and more information about the transition from smoldering-to-flaming, an accurate computational model can also be developed to predict this phenomena.

Appendix

Table 4: Times to smoke/ignition for Cotton Fabric / Cotton Batting / Non-FR Polyurethane Foam, Cotton Fabric / Polyester Batting / Non-FR Polyurethane Foam, and Polyester Fabric / Polyester Batting / Non-FR Polyurethane Foam

Date	Outer Layer	Middle Layer	Inner Layer	Relative Humidity (%)	Temperature (F)	Time to First Wisps (min)	Time to Ignition (min)	Notes
2/25/2019	Cotton Fabric	Cotton Batting	Non-FR Foam	15	60	3:24	31	
2/25/2019	Cotton Fabric	Cotton Batting	Non-FR Foam	15	60	3:22	37	
2/25/2019	Cotton Fabric	Cotton Batting	Non-FR Foam	15	61	3:00	45	
2/26/2019	Cotton Fabric	Cotton Batting	Non-FR Foam	15	61	3:22	43	
2/26/2019	Cotton Fabric	Cotton Batting	Non-FR Foam	15	59	3:16	33	
2/26/2019	Cotton Fabric	Polyester Batting	Non-FR Foam	15	59	3:16	24	
2/26/2019	Cotton Fabric	Polyester Batting	Non-FR Foam	15	59	3:22	N/A	Smoke stops at 40:00
2/26/2019	Cotton Fabric	Polyester Batting	Non-FR Foam	15	58	3:08	N/A	Smoke stops at 53:00
3/7/2019	Cotton Fabric	Polyester Batting	Non-FR Foam	15	48	3:30	42	
3/7/2019	Cotton Fabric	Polyester Batting	Non-FR Foam	15	48	3:06	N/A	Smoke stops at 45:00
3/7/2019	Polyester Fabric	Polyester Batting	Non-FR Foam	15	52	10:34	N/A	Only ever had wisps occasionally. Test was ended after 1 hr
3/7/2019	Polyester Fabric	Polyester Batting	Non-FR Foam	15	54	7:49	N/A	Small wisps of smoke the entire time. Test was ended after 1 hr
3/7/2019	Polyester Fabric	Polyester Batting	Non-FR Foam	15	53	5:25	N/A	Small wisps of smoke the entire time. Test was ended after 1 hr. Fan was on the entire time.
4/15/2019	Polyester Fabric	Polyester Batting	Non-FR Foam	32	66	5:03	N/A	Barely smoked at all. Stopped test at 1 hr
4/16/2019	Polyester Fabric	Polyester Batting	Non-FR Foam	30	67	4:16	N/A	Barely smoked at all. Stopped test at 1 hr

Table 5: Times to smoke/ignition for Cotton Fabric / Cotton Batting / FR (FMVSS 302) Polyurethane Foam, Cotton Fabric / Polyester Batting / FR (FMVSS 302) Polyurethane Foam, and Polyester Fabric / Polyester Batting / FR (FMVSS 302) Polyurethane Foam

Date	Outer Layer	Middle Layer	Inner Layer	Relative Humidity (%)	Temperature (F)	Time to First Wisps (min)	Time to Ignition (min)	Notes
4/1/2019	Cotton Fabric	Cotton Batting	FR Foam	15	64	3:16	45	
4/1/2019	Cotton Fabric	Cotton Batting	FR Foam	15	65	2:50	30	
4/1/2019	Cotton Fabric	Cotton Batting	FR Foam	15	64	2:56	38	
4/16/2019	Cotton Fabric	Cotton Batting	FR Foam	30	67	4:43	38	
4/16/2019	Cotton Fabric	Cotton Batting	FR Foam	32	67	2:50	31	
4/1/2019	Cotton Fabric	Polyester Batting	FR Foam	15	62	5:13	N/A	Smoke stops at 40:00
4/1/2019	Cotton Fabric	Polyester Batting	FR Foam	15	63	2:57	N/A	Smoke stops at 32:00
4/1/2019	Cotton Fabric	Polyester Batting	FR Foam	15	64	2:57	N/A	Smoke stops at 43:00
4/16/2019	Cotton Fabric	Polyester Batting	FR Foam	33	67	3:12	N/A	Barely smoked at all / Stopped test at 1 hr
4/15/2019	Cotton Fabric	Polyester Batting	FR Foam	33	67	2:58	N/A	Barely smoked at all / Stopped test at 1 hr
4/2/2019	Polyester Fabric	Polyester Batting	FR Foam	15	62	11:00	N/A	Stopped test at 1 hr / Melts 1cm into foam
4/2/2019	Polyester Fabric	Polyester Batting	FR Foam	15	63	3:30	N/A	Stops test at 50 min / Melts 1cm into foam
4/18/2019	Polyester Fabric	Polyester Batting	FR Foam	60	66	5:36	N/A	Stopped test at 1 hr, Smoke stopped much earlier
4/18/2019	Polyester Fabric	Polyester Batting	FR Foam	60	67	3:25	N/A	Stopped test at 1 hr, Smoke stopped much earlier
4/18/2019	Polyester Fabric	Polyester Batting	FR Foam	59	69		N/A	Stopped test at 1 hr, Smoke stopped much earlier

Table 6: Times to smoke/ignition for Non-FR Polyester-Cotton Fabric / Cotton Batting / Non-FR Polyester-Cotton Fabric / Cotton Batting / FR (FMVSS 302) Polyurethane Foam and Non-FR Polyester-Cotton Fabric / Cotton Batting / Non-FR Polyurethane Foam

Date	Outer Layer	Middle Layer	Inner Layer	Relative Humidity (%)	Temperature (F)	Time to First Wisps (min)	Time to Ignition (min)	Notes
4/11/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	Non-FR Foam	34	66	2:58	49	
4/11/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	Non-FR Foam	35	66	2:57	N/A	Smoke stops at 53:00
4/11/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	Non-FR Foam	37	66	3:02	40	
4/11/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	Non-FR Foam	38	65	2:52	49	
4/11/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	Non-FR Foam	39	64	3:05	39	
4/15/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	FR Foam	48	69	2:59	N/A	Smokes a lot then Smoke stops at 1hr
4/15/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	FR Foam	42	68	3:05	N/A	Smokes a lot then Stopped test at 1 hr
4/15/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	FR Foam	39	67	1:28	N/A	Barely smoked at all Stopped test at 1 hr
4/15/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	FR Foam	38	67	3:00	N/A	Barely smoked at all Stopped test at 1 hr
4/15/2019	Non-FR Polyester\Cotton Blend Style LOT#9906 STYLE#743.6M	Cotton Batting	FR Foam	36	67	2:57	N/A	Smoke stops at 55:00

Table 7: Times to smoke/ignition for BS 5852 FR Polyester-Cotton Fabric / Cotton Batting / Non-FR Polyurethane Foam and Cotton Fabric / Cotton Batting / FR (BS 5852) Polyurethane Foam

Date	Outer Layer	Middle Layer	Inner Layer	Relative Humidity (%)	Temperature (F)	Time to First Wisps (min)	Time to Ignition (min)	Notes
5/3/2019	FR Polyester/Cotton Blend Style (Passes BS 5852)	Cotton Batting	Non-FR Foam	68	70	2:00	N/A	Smokes a little for the whole hour
5/3/2019	FR Polyester/Cotton Blend Style (Passes BS 5852)	Cotton Batting	Non-FR Foam	71	70	1:57	N/A	Smokes a little for the whole hour
5/3/2019	FR Polyester/Cotton Blend Style (Passes BS 5852)	Cotton Batting	Non-FR Foam	72	70	1:50	N/A	Smokes a little for the whole hour
				76	70	2:22	N/A	Was still smoking after 1hr. Once removed from the apparatus, it began smoking profusedly and showed the sample glowing red hot
5/3/2019	FR Polyester/Cotton Blend Style (Passes BS 5852)	Cotton Batting	Non-FR Foam	77	72	2:20	N/A	Smokes a little for the whole hour
5/6/2019	Cotton Fabric	Cotton Batting	BS 5852 FR Foam	63	69	3:05	N/A	Smokes similarly to Control FR Foam
5/6/2019	Cotton Fabric	Cotton Batting	BS 5852 FR Foam	61	70	3:24	N/A	Smokes similarly to Control FR Foam
5/6/2019	Cotton Fabric	Cotton Batting	BS 5852 FR Foam	59	71	3:08	N/A	Smokes similarly to Control FR Foam
5/6/2019	Cotton Fabric	Cotton Batting	BS 5852 FR Foam	65	71	3:13	N/A	Smokes similarly to Control FR Foam
5/6/2019	Cotton Fabric	Cotton Batting	BS 5852 FR Foam	67	71	3:05	N/A	Smokes similarly to Control FR Foam

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