

Studying smoldering to flaming transition in polyurethane furniture subassemblies: Effects of fabrics, flame retardants, and material type

Alexander B. Morgan¹  | Graham Knapp² | Stanislav I. Stoliarov²  | Sergei V. Levchik³ 

¹Center for Flame Retardant Material Science, University of Dayton, Dayton, Ohio

²Department of Fire Protection Engineering, University of Maryland, College Park, Maryland

³ICL-IP America, Tarrytown, New York

Correspondence

Alexander B. Morgan, Center for Flame Retardant Material Science, University of Dayton, 1700 South Patterson Blvd., Dayton, OH.

Email: alexander.morgan@udri.udayton.edu

Funding information

American Chemical Council - North American Flame Retardant Alliance

Summary

The transition from smoldering to flaming was studied on fabric, batting, and foam assemblies via an electric spot ignition source of similar intensity to a cigarette. The materials studied included four different fabrics (cotton, polyester, cotton/polyester blend, flame retardant cotton/polyester blend), two types of batting (cotton, polyester), and three types of polyurethane foam (nonflame retardant, flame retardant by FMVSS 302 testing, flame retardant by BS5852 testing). The results from testing found that materials highly prone to smoldering could propagate smoldering into foams and lead to ignition, whereas materials that tended to melt back from the ignition source did not. Flame retardant fabrics or foam can and do prevent the transition from smoldering to flaming provided sufficient levels of flame retardants are incorporated in the upholstery fabric or foam. The transition from smoldering to flaming of cotton fabric/nonflame retardant foam assembly was also studied using temperature measurements and evolved gas analysis. It was determined that the transition takes place when the oxygen consumption by accelerating smoldering front exceeds the oxygen supply. At this point, the solid fuel gasification becomes driven by thermal decomposition rather than by surface oxidation which leads to high enough concentrations of fuel for flaming combustion to occur.

KEYWORDS

furniture, ignition, polyurethane foam, smoldering, testing

1 | INTRODUCTION

Through its analysis of fire loss statistics, the National Fire Protection Association (NFPA) recognizes upholstered furniture fires as the deadliest fires in the United States.¹ Fire statistics also point to smoldering objects, mostly cigarettes, as being a primary ignition source of upholstered furniture. Existing fire tests for furniture in the United States (NFPA 260, 261, ASTM E1353, California Technical Bulletin 117, UFAC) are solely focused on resistance to smoldering ignition sources, which may not capture that the real danger of furniture fires is associated with transition from smoldering to flaming combustion,

which eventually can lead to flashover and notable fire loss, including death. Extensive testing of mattresses and bedding materials by the United States Consumer Product Safety Commission (CPSC) showed no correlation between ASTM E1353 and transition to flaming.² There have been numerous studies looking at the phenomena of smoldering to flaming transition for a wide range of materials,³⁻¹⁸ but very few have focused solely on furniture and its relevant components, nor have they studied how the combination of furniture materials (fabric, padding, foam) interact with one another to lead to flaming ignition when a spot ignition source is present. Work by NIST found that airflow was a key factor in the transition from smoldering

to flaming for furniture assemblies tested under ASTM E1353.¹⁹ The results from NIST led the authors of this report to study fabric + foam assemblies in the vertical orientation, exposed to an electric mimic of a cigarette heat source, which was found to reasonably predict the transition from smoldering to flaming for simple fabric + foam combinations.²⁰ It is clear that material composition/chemistry will affect whether materials transition from smoldering to flaming, but being able to reproducibly assess this so that material scientists can better understand what material combinations transition to flaming is still an unmet need. Existing studies focusing on polyurethane smoldering behavior use different methods to force smoldering to transition, making comparisons across materials difficult and unlikely to translate into fire safe material development or commercial use. Thus, there is a need for a method which can be standardized to study smoldering behavior in a comparable way, and can be used to identify material combinations that may impair fire safety by accelerating the transition from smoldering to flaming. Previous work conducted looked at simple fabric and foam combinations,²⁰ and in this work more complex combinations of fabric, batting, and foam were studied in regards to their potential to transition to flaming when exposed to an electric spot ignition source of 11 W which simulates a cigarette ignition source. With regulations in the United States mandating the use of reduced ignition propensity (RIP) cigarettes, one could ask if the 11 W source reflects a RIP cigarette ignition source. It should be noted that recent results indicate RIP cigarettes have some effect on reducing fires vs non-RIP cigarettes, but, fires still occur even with the use of RIP cigarettes.²¹⁻²⁵ This would suggest these cigarettes (RIP and non-RIP) are of equal heat intensity, and therefore we believe that the 11 W source in this article would also simulate a RIP cigarette as well, but this would need to be verified.

While smoldering phenomena have been well studied to date, the transition from smoldering to flaming in the current experimental setup, which was designed to represent the worst case scenario for a smoldering fire on upholstered furniture,²⁰ was not. To achieve better understanding of this transition, measurements of temperature as well as local gas compositions (O₂, CO, CO₂) were collected along the path of smoldering front propagation. Based on the results of these measurements, a hypothesis for the transition mechanism was formulated.

2 | MATERIALS AND EXPERIMENTAL METHODS

All fabrics and battings in this test report were obtained from Test Fabrics (<https://www.testfabrics.com/>). BS 5852 flame retardant fabric and all PU foam samples were provided by Israeli Chemical Limited (ICL). Details on the materials tested is shown below in Table 1.

All foams and fabrics listed in Table 1 above were conditioned in an enclosed 30.5 cm × 50.8 cm × 60.9 cm (12" × 20" × 24") tank with desiccants (Drierite) for at least 24 hours before experimentation. The desiccants kept the conditioning tank at about 20% humidity. Fresh desiccants are added as necessary. The material combinations that were tested are shown in Table 2.

TABLE 1 Fabric, batting, and foam product details and information

Material	Product details/Vendor information
Cotton fabric	Beige cotton velvet, Product # 8500
Cotton batting	Product # 1504008
Polyester fabric	Hercules 175 g (6.2 oz), Style 700-7. Product # 1411009
Polyester batting	Product # 804003
Cotton/ polyester fabric	65% polyester, 35% cotton, bleached with durable press finish (with optical brightener), Lot# 9906, Style 7436 M
Cotton/ polyester FR fabric	Rated to pass BS 5852, ignition source #1 (match) fire test performance verified by ICL. Vendor not known, but material showed an areal weight of 400 g/m ² , and contained 7.5 wt% Br, and had 5.5 wt% Sb ₂ O ₃ . The exact flame retardant used on this commercial fabric was 8.8% decabromodiphenylethane
PU foam	Density 30.4 kg/m ³ (1.9 lb/ft ³). Air flow 0.7 standard cubic feet per minute (scfm). Was found to fail FMVSS 302 testing, no flame retardant was detected. This foam will be referred to as "NFR Foam" in the text
FR (FMVSS 302) foam	Density 28.8 kg/m ³ (1.8 lb/ft ³). Air flow 1.6 scfm. Was found to pass FMVSS 302 testing with a SE/NBR rating, contained 0.47 wt% P which translates to 5 wt% nonhalogenated phosphorus-based flame retardant. This foam will be referred to as "lightly flame retarded" in the text
FR (BS 5852) foam	Density 22.4 kg/m ³ (1.4 lb/ft ³). Air Flow 0.7 scfm. Contained 0.87 wt% P and 3 wt% Cl which translates to 9.2 wt% tri-(1-chloropropyl)phosphate (TCPP) flame retardant. Material reported to pass BS5852, crib #5 ignition source and is believed to contain melamine as well, but independent chemical analysis for melamine content could not be confirmed. This foam will be referred to as "heavily flame retarded" in the text

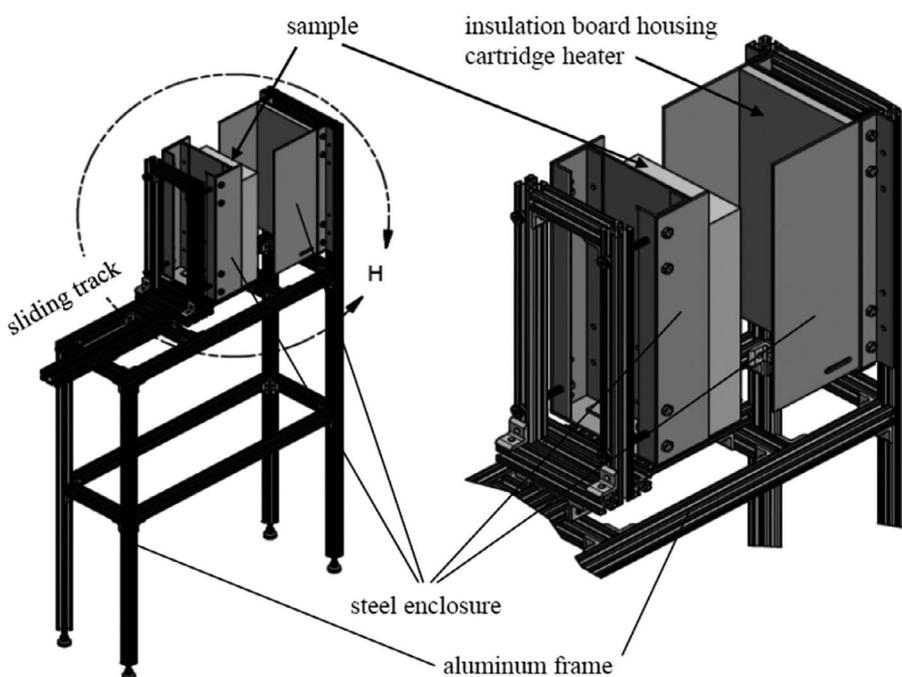
All testing was carried out using the apparatus which is described in detail in a previous publication,²⁰ but a synopsis of the test method used is outlined here to better communicate the test method and the results obtained in this article.

First, the fabric, batting, and foam are first conditioned, and then assembled in a standard way to yield an assembly which is held in place with wire nails to a ceramic fiber insulation board (Figure 1) where the fabric is on the outside, the padding is directly underneath the fabric, and the foam is under the padding.

The samples were mounted in the smoldering apparatus shown in Figure 2. The smoldering apparatus was placed under a 500 kW exhaust hood. The position of the apparatus was selected to minimize forced airflow in its vicinity (<0.3 m/s), while providing adequate removal of the combustion products.

TABLE 2 Fabric/batting/foam combinations for smoldering to flaming transition testing

Outer fabric	Batting	Foam type	Abbreviation
Cotton	Cotton	PU foam	Cot/Cot/NFR foam
Cotton	Polyester	PU foam	Cot/Poly/NFR foam
Polyester	Polyester	PU foam	Poly/Poly/NFR foam
Cotton	Cotton	FR (FMVSS 302) PU foam	Cot/Cot/FMVSS 302 FR foam
Cotton	Polyester	FR (FMVSS 302) PU foam	Cot/Poly/FMVSS 302 FR foam
Polyester	Polyester	FR (FMVSS 302) PU foam	Poly/Poly/FMVSS 302 FR foam
Cotton/polyester	Cotton	PU foam	Cot-Poly/Cot/NFR foam
Cotton/polyester	Cotton	FR (FMVSS 302) PU foam	Cot-Poly/Cot/FMVSS 302 FR foam
Cotton/polyester FR fabric	Cotton	PU foam	FR Cot-Poly/Cot/NFR foam
Cotton	Cotton	FR (BS 5852) PU foam	Cot/Cot/BS5852 FR foam

**FIGURE 1** Typical sample pinned to a ceramic fiber insulation board [Colour figure can be viewed at wileyonlinelibrary.com]**FIGURE 2** A three-dimensional rendering of the smoldering apparatus

The following testing procedure was followed. After recording the air temperature and humidity in the testing facility, a sample removed from the desiccator was mounted inside the apparatus and the minimum gap between the sample and the insulation board was adjusted to 0.7 cm. The cartridge heater was turned on by supplying 11 W DC to start the experiment and the time of appearance of a visible flame was recorded. In the absence of flame, the heater was powered continuously for 45 minutes. The experiment was terminated after a transition to flaming took place or after the smoldering process stopped, which was inferred from the absence of smoke emanating from the enclosure. If the transition did take place, the flame was suppressed using a carbon dioxide extinguisher.

The facility where these tests were performed was not climate controlled, so the air temperature and relative humidity varied between 14°C and 24°C and 40%-60%, respectively over the period of the experimental campaign. 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 tested.

The types of experiments that focused on temperature and gas measurements relevant to the transition from smoldering to flaming in a control-material setup used the configuration shown in Figure 3. This figure gives a visual representation of what the sample setup for these types of experiments looks like within the stainless steel housing of the smoldering apparatus used for this work. Similar to the experiments utilizing the previously published method,²⁰ which focused on the impact of various materials on the transition probability, the experiments for temperature and gas measurements also have a sample, represented by a polyurethane foam block covered with the cotton fabric (not shown in Figure 3), which is mounted on a Ceramic Fiber Insulation Board. The sample creates a small (about 0.7 cm) gap with the opposing insulation board, and the cartridge heater powered with 11 W DC and pressed into the sample (about 1 cm deep) is used to initiate the smoldering

process. The sample is mounted vertically. The gas flow through the gap is driven only by buoyancy. A gas probe that collects the gases within the gap is inserted along with thermocouples, which beads were located just inside the gap (no more than 2 mm into the gap) at a range of heights, as shown in Figure 3. The gas probe did not touch the surface of the sample so that it could be moved up and down during testing to collect gases at the thermocouple locations. Gas sampling was collected at each of the thermocouple locations to measure gas concentrations at that spot above the ignition source during the test. The gas analyzer used was a ZPA Infrared Gas Analyzer (ZPA3—California Analytical Instruments), which used a vacuum pressure pump (Cole Parmer) that sampled gases at 1.5 L/min. A United Filtration 316 L SS/Glass filter housing with coalescing cartridge (0.01 µm) was used to remove moisture and large particulates from the gas streams prior to the gases reaching the gas analyzer, which measured CO₂, CO, and O₂ during the test. Baseline calibrations with nitrogen gas, and a gas mixture of nitrous oxide, 8.238 vol% CO₂, 0.8291 vol% CO were used to calibrate the CO₂ and CO sensors. Air from the room was used to calibrate the O₂ sensor. OMEGA fine wire (0.125 mm) thermocouples (type K) were used to collect temperatures while connected to a Fluke 2645A Net Data Acquisition Unit which was connected to a laptop with data collection software during testing.

3 | RESULTS

3.1 | Effects of material combinations on transition from smoldering to flaming

Before discussing the results obtained in this article, it should be pointed out that for seat backs in consumer furniture today, combinations of just fabric and polyurethane foam are not used except in much

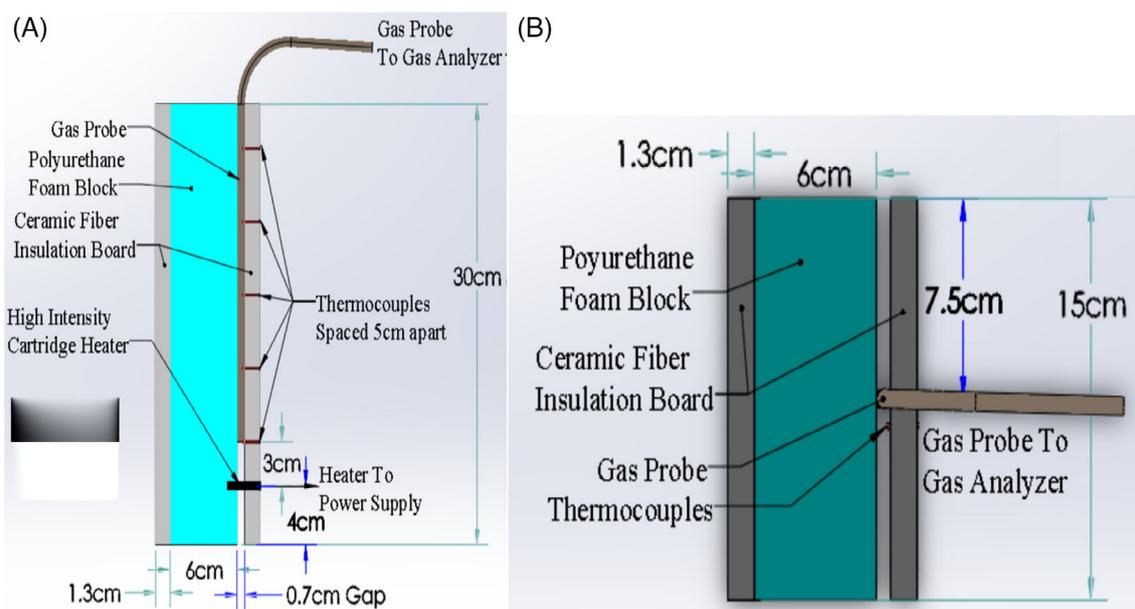


FIGURE 3 The fabric/foam assembly geometry in position within the smoldering apparatus with the addition of five thermocouples and a gas probe between the sample and the opposing insulation board. A, Cross section of the side view. B, Top view [Colour figure can be viewed at wileyonlinelibrary.com]

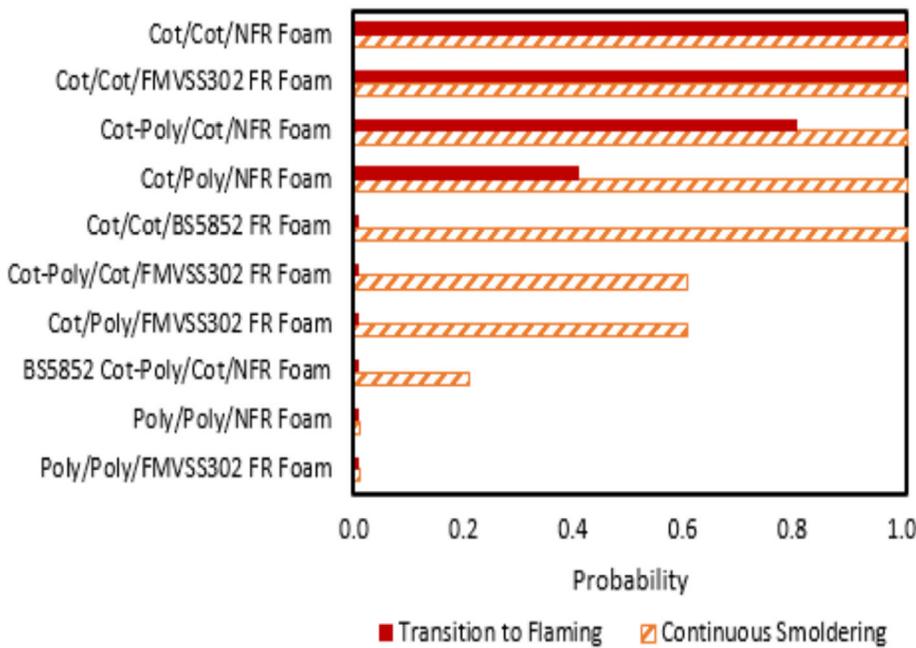


FIGURE 4 Summary data for transition from smoldering to flaming behavior for samples tested. The probability is calculated based on five repeated tests [Colour figure can be viewed at wileyonlinelibrary.com]

older furniture or in cases where the consumer has chosen to reupholster the furniture. Otherwise, throughout the furniture combinations of fabric, batting, and foam are present (seat cushions), or just fabric and batting (seat backs, arm rests). To better understand the versatility of the test method previously developed, combinations of fabric, batting, and foam were combined and tested via the previously published experimental protocol. Further, materials other than cotton were studied as polyester and cotton/polyester materials are more commonly used in United States furniture than just cotton alone. It should be noted that because flame retardant furniture foam has not been available in the United States since 2013, FMVSS 302 automotive foam was selected for this study to represent lightly flame retardant foam, and BS5852 materials were selected for this study to represent flame retardant foam and fabric designed to pass stricter fire tests.

Each of these material combinations, where the outer fabric was first exposed to the ignition source, were tested a total of five times, with the binary result of transition to flaming/nontransition to flaming recorded. Smoke being produced (confirmed via obvious visual observation during the test) was assumed to be directly related to continuing smoldering during the test, and is recorded as “continuous smoldering” in Figure 4 below. Acronyms for the abbreviations and details on the materials used are in Table 2.

With the results in Figure 4, there are some high level conclusions that can be made.

- Those material combinations that do not exhibit continuous or sustained smoldering throughout the duration of the test (about 50 minutes) never transition to flaming.
- Not all materials that do exhibit continuous smoldering undergo the transition.

- The presence of polyester batting (Poly) will greatly reduce the chances for transition to flaming.
- Cotton batting greatly increases the chances for transition to flaming.
- Cotton fabric + cotton batting can overwhelm lightly flame retarded FMVSS 302 rated FR foam.
- Flame retarded BS5852 foam will resist the transition to flaming, even when strong smoldering materials (cotton fabric and cotton batting) are present.
- Flame retarded BS5852 textile prevents transition to flaming even when cotton batting/NFR foam is used.

Some additional details and experimental observations on each material combination are given below to interpret the results for each of the 10 material combinations, and to give some additional details on what physical behavior was observed during testing.

3.1.1 | Cotton fabric/cotton batting/NFR PU foam (Cot/Cot/NFR foam)

Cotton is well known to be a material with a propensity to smoldering due to its chemical structure (cellulosic—charring with low heat release).²⁶⁻²⁸ After five tests the material always transitioned to flaming within 31 to 45 minutes after exposure to the heat source. Smoke was always observed within 3 minutes of exposure to the heat source. This 100% chance of transition to flaming indicates that cotton materials placed upon nonflame retardant foam, if ignited with a smoldering based ignition source, will likely result in fire events.

3.1.2 | Cotton fabric/cotton batting/FMVSS 302 FR PU foam (Cot/Cot/FR foam)

As discussed above, the presence of cotton fabric and cotton batting always led to a transition from smoldering to flaming when non-FR (NFR) foam was used, and when FR PU foam was used, again the sample ignited five out of five times. Time to the observation of smoke was a bit more variable than when the NFR foam was used (2-4 minutes), and time to ignition showed some variability as well (30-45 minutes), but overall, the materials always ignited. The FR foam was only rated to Federal Motor Vehicle Safety Standard (FMVSS) 302, which is a fire safety standard that only protects against small open flame sources. Clearly the strong smoldering behavior of the cotton overwhelms the flame retardant present in the foam, resulting in high probabilities (five out of five in this case) for transition to flaming.

3.1.3 | Cotton-polyester fabric/cotton batting/NFR PU foam (Cot-Poly/Cot/NFR foam)

Cotton-polyester fabrics are very common in furniture assemblies, and when this fabric type is combined with cotton batting and NFR PU foam, the material assembly transitioned to flaming four out of five times. Smoke production observation was very consistent (first observed around 3 minutes) and the time to ignition was between 39 and 49 minutes for the four samples that ignited.

3.1.4 | Cotton fabric/polyester batting/NFR PU foam (Cot/Poly/NFR foam)

The presence of polyester batting, which is a thermoplastic material that can melt away from a heat source, greatly affects the transition to flaming even when a smoldering material (cotton fabric) is present as the first material exposed to the heat source. Only two of the five samples tested transitioned to flaming, and, for the samples that did not ignite, they also stopped releasing smoke during the test, indicating that the polyester batting was inhibiting the smoldering transitioning to flaming. This phenomena with the polyester batting will be discussed in more detail below. All of the samples began to show smoke within 3 minutes of exposure, but the times to flaming ignition were highly variable (24 and 42 minutes).

3.1.5 | Cotton fabric/cotton batting/BS 5852 FR PU foam (Cot/Cot/BS5852 FR foam)

Previous testing of the cotton fabric and cotton batting with NFR and FMVSS 302 FR foam always resulted in transition to flaming. However, when highly flame retardant foam (foam flame retarded to British Standard 5852), this material combination did not transition to flaming. Smoke was observed around 3 minutes for all samples.

3.1.6 | Cotton-polyester fabric/cotton batting/FMVSS 302 FR PU foam (Cot-Poly/Cot/FR foam)

Use of lightly flame retarded foam prevented the transition to flaming in five out of five samples when used with cotton-polyester fabric and cotton batting. There was some variability in time to first smoke production (1-3 minutes), and in total volume of smoke produced by some of the samples, which suggests there may be some other physical effects going on with this combination that may merit further post-test analysis to determine why some samples smoked heavily and others did not. Since the samples were highly degraded by the end of the test, this further post-test analysis was not conducted and will be studied in future work.

3.1.7 | Cotton fabric/polyester batting/FMVSS 302 FR PU foam (Cot/Poly/FR foam)

In the presence of FR PU foam, the combination of cotton fabric and polyester batting did not transition to flaming, compared to a material which did transition to flaming two out of five times when NFR PU foam was used. While the lightly flame retarded foam was overwhelmed when cotton fabric and batting was used, in the presence of the polyester batting, transition to flaming did not occur and perhaps the flame retardant helped reduce the remaining chances of ignition to zero.

3.1.8 | BS 5852 FR cotton-polyester fabric/cotton batting/NFR PU foam (FR Cot-Poly/Ct/NFR foam)

When a flame retarded (British Standard 5852) cotton-polyester fabric was used with cotton batting and NFR foam, the materials never transitioned to flaming. Initial smoke was observed within 2 minutes of exposure to the heat source, but the rate of smoke release was low throughout the test. One of the samples however, showed continual smoke release even after 1 hour of testing, and did show some continuing red-hot smoldering present deep in the sample after removal from the apparatus (visual observation), suggesting that if the smoldering zone propagates past the surface fabric, there could be some lingering concern of long-term smoldering even if the material never ignited.

3.1.9 | Polyester fabric/polyester batting/NFR PU foam (Poly/Poly/NFR foam)

The polyester fabric and batting are thermoplastic materials which can melt away from heat sources, and this observed behavior prevented transition to flaming in five out of five samples tested (Figure 4). Smoke production was delayed compared to the samples containing cotton, and in some cases the sample assemblies produced very little smoke when humidity was higher during testing. Since the samples

did not ignite and showed localized thermal damage after testing, analysis of the sample pulling back the damaged layers was conducted. This showed that the polyester melted back to form air gaps around the heat source which prevented smoldering. While the polyester fabric, batting, and NFR PU foam all showed thermal damage and decomposition, it is clear that eventually chars were set up that would not decompose further, and thus no ignition occurred (Figure 5). The fact that polyester is a thermoplastic material is why this behavior is observed. Specifically, when exposed to a spot source 11 W heat, the polyester “melts back” to some distance away from the spot heat source until it resolidified. Prolonged heat exposure from the 11 W heat source causes the polyester to thermally decompose and char, but not decompose with sufficient gas release to cause an ignition, hence the clear thermal damage and “hole” as seen in Figure 5 which cannot propagate the heat damage further into the polyurethane foam. Cotton does not melt back, and hence when it chars and undergoes smoldering, will continue to be in contact with the polyurethane foam, thus increasing the chance of ignition from the smoldering cotton. It should be noted that polyester, even though it is melting away from the heat source, is a flammable material, and while it appears to be providing fire protection by melting away from the heat source, it may transition to fire events in other orientations.

3.1.10 | Polyester fabric/polyester batting/FMVSS 302 FR PU foam (Poly/Poly/FR foam)

Similar to the results when NFR foam was used (Table 2), this material combination showed no transition to flaming. Similar thermal damage was observed for this material where a small thermally decomposed

“hole” was observed in the outer layer of fabric and inner batting, and pushing into the foam, but the char that formed did not propagate into flaming (see Figure 5).

The overall results collected on these combinations of materials show that material combination matters in the transition from smoldering to flaming. How a material will hold onto heat and propagate a smoldering front into more flammable materials (polyurethane foam) will determine the probability of flaming ignition, and likewise, if a material can melt back from a heat source, it is more likely to create an air gap that prevents the smoldering material from reaching the more flammable polyurethane foam. In modern furniture today, there are seat backs that have no polyurethane foam present at all, and how those materials would perform against such a heat source suggests that they will just melt away from the heat source. However, polyester is a flammable material, and this should be verified rather than assumed to see if looser polyester fiber-fill padding, rather than the thicker polyester batting used in this article, would indeed result in expected melt back behavior, or fire events.

3.2 | Detailed analysis of the transition from smoldering to flaming

The analysis of transition was performed using a simple cotton fabric + NFR PU foam configuration, which transitioned from smoldering to flaming with a probability of 70%²⁰ and provided the maximum control of the sample geometry. The presented data were collected in five repeated tests, in all of which the transition to flaming took place. Visual observations showed six stages including (a) small wisps of smoke, (b) growing wisps of smoke (c) initial smoke plume formation



FIGURE 5 Polyester fabric/polyester batting/NFR PU foam sample: outer layer (left), middle layer (middle), inner layer (foam) [Colour figure can be viewed at wileyonlinelibrary.com]

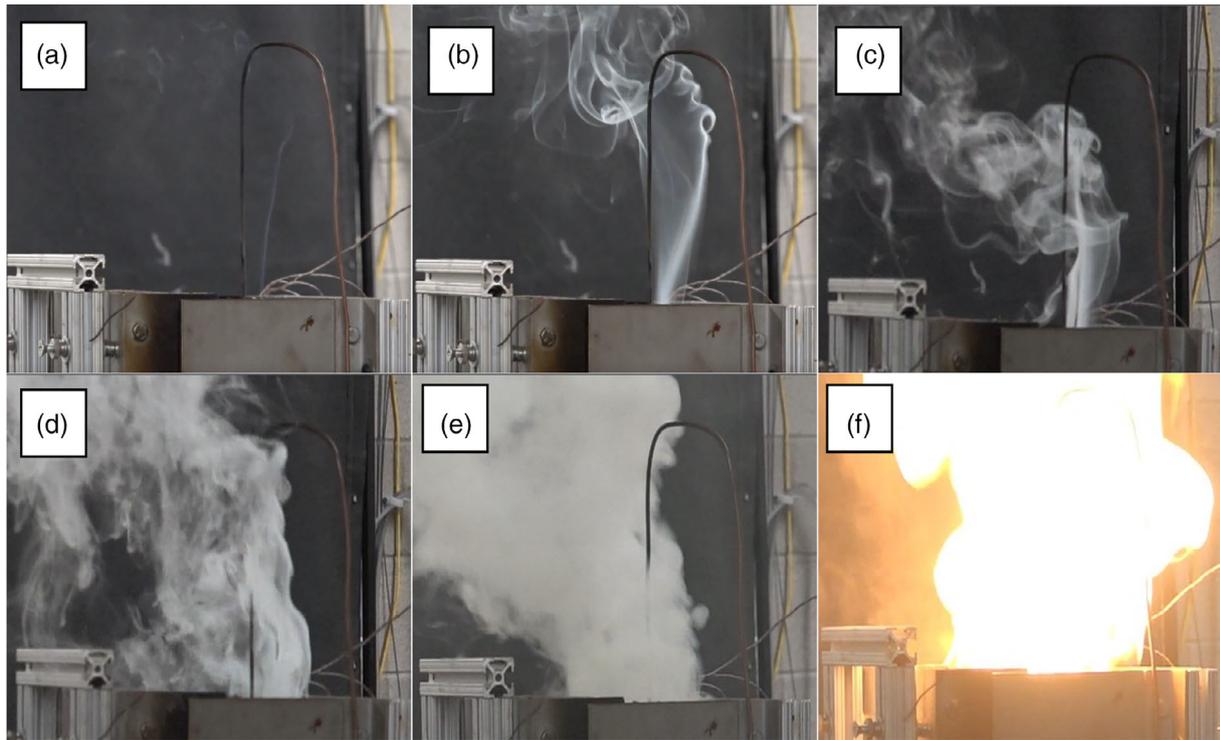


FIGURE 6 Six visually observed stages of smoldering leading to flaming transition [Colour figure can be viewed at wileyonlinelibrary.com]

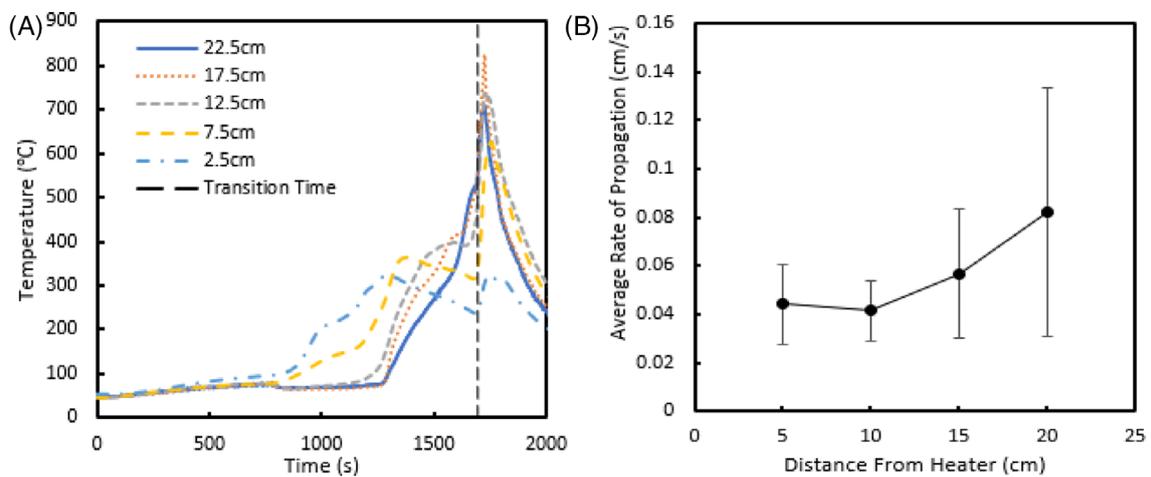


FIGURE 7 A, Temperature profiles at various distances from the ignition source collected in a single representative test on cotton fabric + NFR PU foam assembly; B, the average rate of smoldering front propagation as a function of the distance from the ignition source [Colour figure can be viewed at wileyonlinelibrary.com]

(d) intensifying smoke plume formation (e) high density smoke plume generation, and (f) transition to flaming. These stages are shown in Figure 6. Not shown in these pictures is the formation of liquified polyurethane decomposition products which would drip from the bottom of the apparatus during the latter half of the test. These decomposition products would ignite and fall out the bottom of the apparatus once the sample ignited.

During the course of testing, thermocouple measurements showed an expected propagation of the smoldering front from the

bottom of the sample upward. Representative temperature profiles showing this, as well as the sudden spike in temperatures at the transition, are given in Figure 7A. As the smoldering front approached a particular thermocouple, its temperature increased. Further, when the smoldering front passed the thermocouple and began to gain distance from it, the temperature reading decreased because the thermocouple was no longer near the smoldering front, where exothermic reactions between oxygen and condensed-phase sample surfaces generated heat. The reason the thermocouples at 12.5, 17.5, and 22.5 cm above

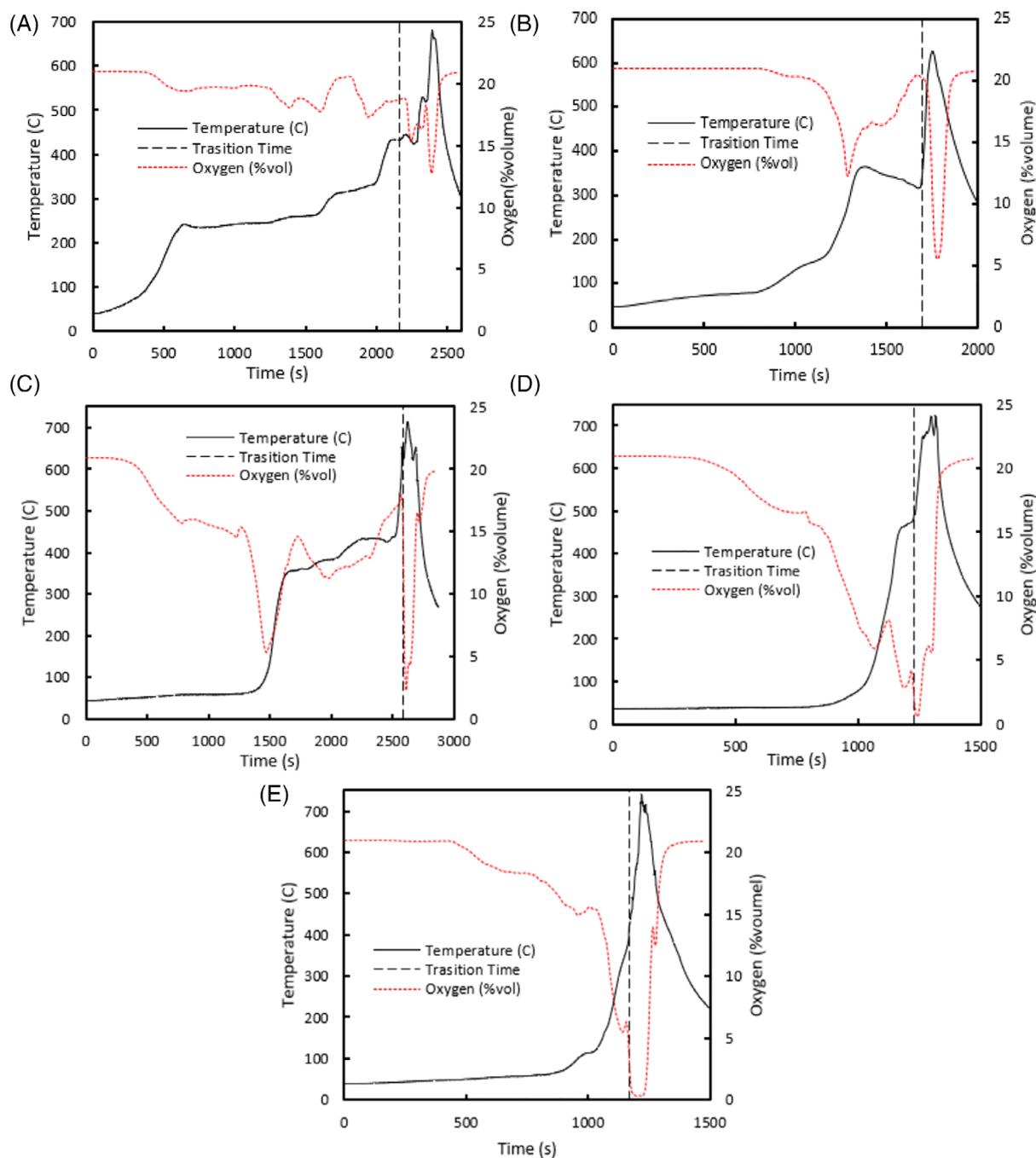


FIGURE 8 O_2 volumetric concentration and temperature profiles collected at: A, 2.5 cm above heater, B, 7.5 cm above heater, C, 12.5 cm above heater, D, 17.5 cm above heater, and E, 22.5 cm above heater. Each O_2 profile was collected in a separate test; that is why the time of transition differs between the graphs [Colour figure can be viewed at wileyonlinelibrary.com]

the heater did not show this decrease as much was because their locations were roughly where the smoldering front reached when the sample transitioned to flaming. Thermal gravimetric analysis of polyurethane in air indicates that the maximum rate of mass loss is achieved at 294°C.²⁹ Here this temperature threshold was used to track the position of the smoldering front in time. These data were subsequently converted to the rate of the front propagation shown in Figure 7B. The average rate of propagation has a positive trend, indicating that, as the smoldering front moved upward, the rate of

propagation increased. The error bars in Figure 7B were calculated using 95% confidence limit and are rather large, which is indicative of the stochastic nature of the smoldering front propagation process.

Considering the above information, the volumetric O_2 concentration data was collected at each of the thermocouple locations to give insight into oxygen consumption in relation with the local gas temperature and smoldering front location. These results are shown in Figure 8; they indicate that, as the smoldering front reaches a particular location, the O_2 concentration at this location decreases. As the

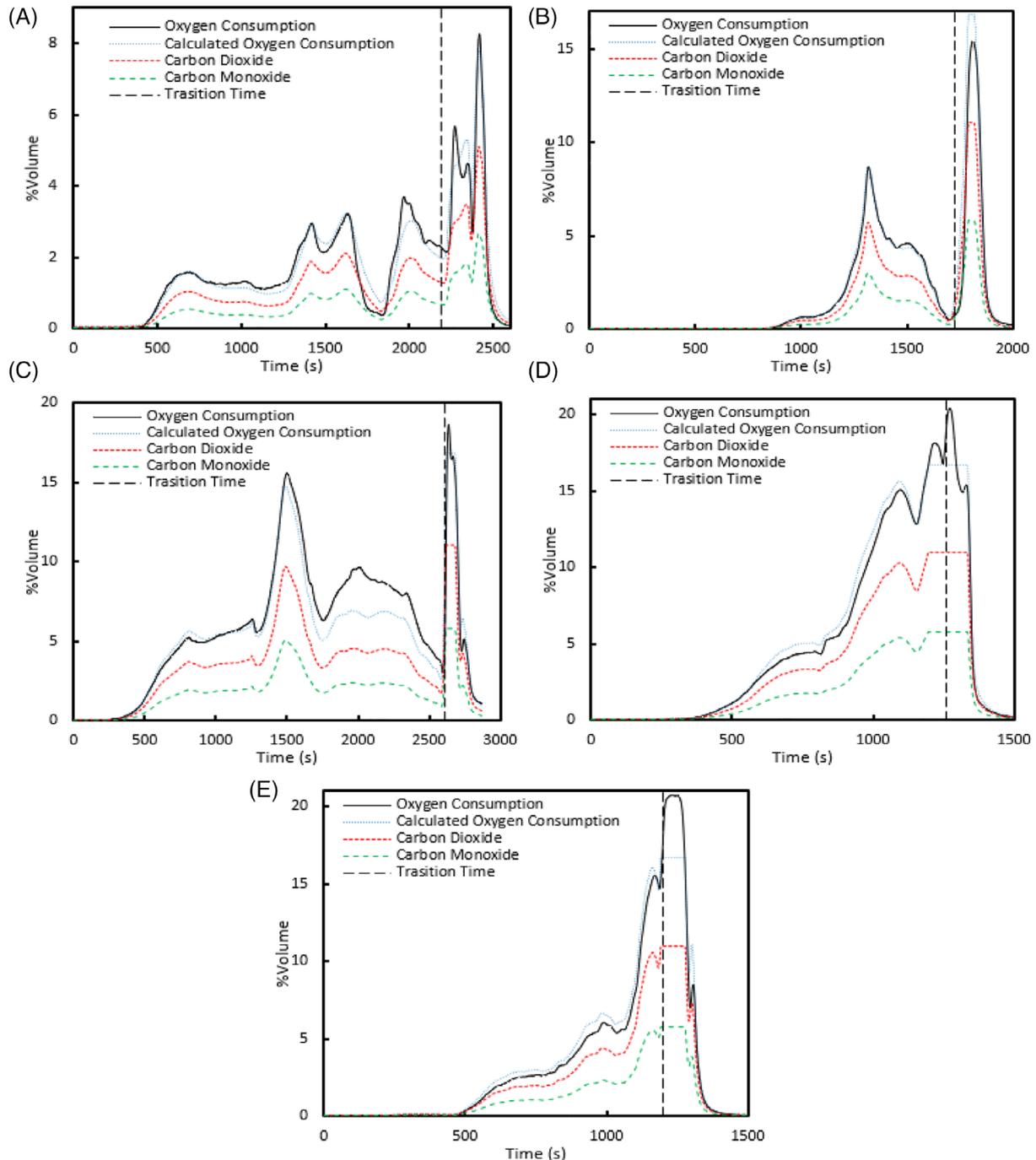


FIGURE 9 CO and CO₂ volumetric concentrations and oxygen consumption profiles collected at: A, 2.5 cm above heater, B, 7.5 cm above heater, C, 12.5 cm above heater, D, 17.5 cm above heater, and E, 22.5 cm above heater. The oxygen consumption curve shown as a semitransparent line labeled “Calculated Oxygen Consumption” was obtained from the CO and CO₂ signals. Each set of gas concentration profiles at a particular distance above the heater was collected in a separate test; that is why the time of transition differs between the graphs [Colour figure can be viewed at wileyonlinelibrary.com]

smoldering front accelerates toward the top of the sample, nearly all oxygen gets consumed at these higher locations (17.5 and 22.5 cm above heater). This nearly complete consumption of O₂ immediately precedes the transition from smoldering to flaming.

Based on these observations, it is the excess heat produced by the smoldering reactions that drives the acceleration of the smoldering front. This acceleration leads to nearly complete consumption of

O₂ at higher elevations of the samples (because of a limited oxygen flow through the gap). A combination of high temperature and absence of oxygen at these elevations produces conditions where the smoldering reactions effectively cease, while the thermal decomposition reactions of the PU foam become dominant. These thermal decomposition reactions are known to generate highly flammable gaseous species.^{30,31}

CO and CO₂ volumetric concentrations are presented as a function of time and location in Figure 9. Some CO₂ profiles level off at 10.9% because they reach the limit of the sensor. CO sensor limit was 1%. The CO data above this limit was obtained by assuming a constant CO/CO₂ ratio, which was, in fact, found to be constant in all tests during the period of time when the CO concentration was still measurable.³² The data presented in the figure also indicates that the oxygen consumption calculated from the CO and CO₂ volumetric concentration profiles closely matches that measured directly using the oxygen sensor. Thus, the smoldering reactions, which by definition involve oxygen, do not produce any other products in significant quantities. Since neither CO nor CO₂ are sufficiently combustible to fuel a diffusion flame, some other process within this system must be responsible for generation of gaseous species that enable transition to flaming.

This observation is further supported by the results of a previous study.²⁰ These results indicate that, when the same cotton fabric + NFR PU foam samples are tested with a wider (about 1.7 cm) gap between the insulating board and the sample, which effectively increases the oxygen supply, the smoldering intensity increases. However, the transition to flaming no longer takes place. It appears that, in the current setup, for the transition to occur, a robust smoldering front development must be followed by a localized depletion of oxygen, which triggers anaerobic thermal decomposition reactions that create the gaseous fuel necessary to initiate the transition. Once this gaseous fuel diffuses to the high temperature regions where oxygen is still abundant and smoldering is still intense, it ignites.

4 | CONCLUSIONS

The materials present between the smoldering ignition source and the nonflame retarded polyurethane foam have a strong effect on this transition to flaming. Specifically, materials which char and cannot melt away from the ignition source (such as cotton) will propagate smoldering fronts into other flammable materials. Those that melt away (such as polyester) will stop smoldering fronts from reaching the polyurethane foam, although smoke will be produced and thermal damage to the flammable polyurethane will still occur near the smoldering ignition source. When charring and melting materials are combined, there will be highly variable melting/decomposition behavior which may or may not allow smoldering to propagate into foams for ignition, and this variability as materials melt away in chaotic fashions is real world behavior.

The results from testing find that the combination of cotton fabric with cotton batting is highly likely to lead to a transition from smoldering to flaming, even in the presence of lightly flame retarded PU foam. Only when highly flame retardant foam is used will the transition to flaming be stopped when using cotton fabrics and cotton batting. Use of polyester batting at sufficient thickness greatly reduces the chances of transition to flaming, and the combination of polyester fabric and polyester batting prevents the transition from smoldering to flaming from occurring. The use of highly flame retardant fabrics or

foams (ie, materials formulated/designed to pass BS5852 testing) can and do suppress the transition from smoldering to flaming, even when exposed to the strongest smoldering ignition source (cotton batting). This result indicates that if sufficient flame retardant is used, even if designed for a high intensity flaming source, it can enhance resistance to a smoldering ignition source as well.³³⁻³⁵ Future work should investigate some of the material combinations where the transition to flaming was irregular, as well as combinations where no polyurethane foam is present. Ignition exposure times and orientation effects of the composite fabric/padding/foam assemblies may also merit future study.

Detailed experimental measurements collected for the basic cotton fabric + NFR PU foam system indicated that the smoldering to flaming transition requires a sustained smoldering front growth that is achieved by delivering sufficient amount of oxygen to a condensed-phase fuel of large specific surface area and by limiting heat losses from the smoldering front. The measurements also indicate that, for the transition to take place in the current setup, it is also necessary for the consumption of oxygen to exceed its supply at some point during the course of the smoldering front growth. This imbalance activates localized anaerobic thermal decomposition of solid fuel, which creates sufficiently high amounts of combustible gases to establish a flame.

It is our hope that this test method which is under continuous development will yield a test method that enables fire safety scientists, fire safety engineers, and material scientists to better understand the fire threats of furniture regardless of the materials that may be used in their construction. This way all researchers will have a standard method of comparing results with one another to better understand the fire risks associated with smoldering ignition sources and smoldering/nonsmoldering high heat release materials.

ACKNOWLEDGEMENTS

The authors would like to thank Olga Zeller and Fernando Raffan-Montoya for guidance on the experimental work. The authors would also like to thank the American Chemical Council, North American Flame Retardant Alliance for funding of this work.

ORCID

Alexander B. Morgan  <https://orcid.org/0000-0003-0905-3224>

Stanislav I. Stolarov  <https://orcid.org/0000-0002-3429-9245>

Sergei V. Levchik  <https://orcid.org/0000-0002-3553-2168>

REFERENCES

1. Ahrens M. Home fires that began with upholstered furniture. *NFPA Research*. Quincy, MA, USA: National Fire Prevention Association; 2017. <https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/US-Fire-Problem/Fire-causes/osupholstered.pdf>. Accessed April 14, 2020.
2. Zammarano M, Matko S, Davis RD. Impact of test and foam design on smoldering. *National Institute of Standards and Technology Technical Note 1799*. Gaithersburg, MD, USA: US National Institute of Standards and Technology; 2013. <https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1799.pdf>. Accessed April 14, 2020.

3. Torero JL, Fernandez-Pello AC. Natural convection smolder of polyurethane foam, upward propagation. *Fire Saf J*. 1995;24:35-52.
4. Chao CYH, Wang JH. Transition from smoldering to flaming combustion of horizontally oriented flexible polyurethane foam with natural convection. *Combust Flame*. 2001;127:2252-2264.
5. Bar-Ilan A, Putzeys OM, Rein G, Fernandez-Pello AC, Urban DL. Transition from forward smoldering to flaming in small polyurethane foam samples. *Proc Combust Inst*. 2005;30:2295-2302.
6. Putzeys O, Bar-Ilan A, Rein G, Fernandez-Pello AC, Urban DL. The role of secondary char oxidation in the transition from smoldering to flaming. *Proc Combust Inst*. 2007;31:2669-2676.
7. Torero JL, Fernandez-Pello AC. Forward smolder of polyurethane foam in a forced air flow. *Combust Flame*. 1996;106:89-109.
8. Putzeys OM, Fernandez-Pello AC, Rein G, Urban DL. The piloted transition to flaming in smoldering fire retarded and non-fire retarded polyurethane foam. *Fire Mater*. 2008;32:485-499.
9. Rein G. Smoldering combustion phenomena in science and technology. *Int Rev Chem Eng*. 2009;1:3-18.
10. Ogle RA, Dillon SE, Fecke M. Explosion from a smoldering silo fire. *Process Saf Prog*. 2014;33:94-103.
11. Russo P, De Rosa A, Mazzaro M. Silo explosion from smoldering combustion: a case study. *Can J Chem Eng*. 2017;95:1721-1729.
12. Ohlemiller TJ. Forced smolder propagation and the transition to flaming in cellulosic insulation. *Combust Flame*. 1990;81:354-365.
13. Tse SD, Fernandez-Pello AC, Miyasaka K. Controlling mechanisms in the transition from smoldering to flaming of flexible polyurethane foam. *Symp (Int) Combust*. 1996;26:1505-1513.
14. Alexopoulos S, Drysdale DD. The transition from smoldering to flaming combustion. *Fire Mater*. 1988;13:37-44.
15. Hagen BC, Frette V, Kleppe G, Arntzen BJ. Onset of smoldering in cotton: effects of density. *Fire Saf J*. 2011;46:73-80.
16. Wang S, You F, Hu S-Q, Zhou Y, Sun W. Effects of bulk densities and inlet airflow velocities on forward smoldering propagation properties of flexible polyurethane foam. *Procedia Eng*. 2018;211:762-767.
17. Hadden R, Alkatib A, Rein G, Torero JL. Radiant ignition of polyurethane foam: the effect of sample size. *Fire Technol*. 2014;50:673-691.
18. Hagen BC, Frette V, Kleppe G, Arntzen BJ. Transition from smoldering to flaming fire in short cotton samples with asymmetrical boundary conditions. *Fire Saf J*. 2015;71:69-78.
19. Zammarano M, Matko S, Pitts WM, Fox DM, Davis RD. Towards a reference polyurethane foam and bench scale test for assessing smoldering in upholstered furniture. *Polym Degrad Stab*. 2014;106:97-107.
20. Stolarov SI, Zeller O, Morgan AB, Levchik S. An experimental setup for observation of smoldering-to-flaming transition on flexible foam/fabric assemblies. *Fire Mater*. 2018;42:128-133. <https://doi.org/10.1002/fam.2464>.
21. Anderson A, Janssens M. A multi-national survey of low-energy and smoking materials ignition fires. *Fire Technol*. 2016;52:1709-1735.
22. Hall JR Jr. *The Smoking Material Fire Problem*. Quincy, MA: National Fire Protection Association; 2013.
23. Alpert HR, Christiani DC, Orav EJ, Dockery DW, Connolly GN. Effectiveness of the cigarette ignition propensity standard in preventing unintentional residential fires in Massachusetts. *Am J Public Health*. 2014;104.
24. Butry DT, Thomas DS. Cigarette fires involving upholstered furniture in residences: the role that smokers, smoker behavior, and fire standard compliant cigarettes play. *Fire Technol*. 2017;53:1123-1146.
25. Yau RK, Marshall SW. Association between fire-safe cigarette legislation and residential fire deaths in the United States. *Inj Epidemiol*. 2014;1:10.
26. Price D, Horrocks AR, Akalin M, Farooq AA. Influence of flame retardant on the mechanism of pyrolysis of cotton (cellulose) fabrics in air. *J Anal Appl Pyrol*. 1997;40:511-524.
27. Galaska ML, Horrocks AR, Morgan AB. Flammability of natural plant and animal fibers: a heat release survey. *Fire Mater*. 2017;41:275-288. <https://doi.org/10.1002/fam.2386>.
28. Hagen BC, Frette V, Kleppe G, Arntzen BJ. Effects of heat flux scenarios on smoldering in cotton. *Fire Saf J*. 2013;61:144-159.
29. Shang W. Laboratory-Scale Evaluation of Aramid Blend Material as a Fire Barrier for Flexible Polyurethane Foam [master's degree (Mechanical Engineering) thesis]. Case Western Reserve University, May 2016. http://rave.ohiolink.edu/etdc/view?acc_num=case1462873811. Accessed April 14, 2020.
30. Kramer RH, Zammarano M, Linteris GT, Gedde UW, Gilman JW. Heat release and structural collapse of flexible polyurethane foam. *Polym Degrad Stab*. 2010;95:1115-1122.
31. Galaska ML, Morgan AB, Schenck KA, Stalter JG. Apparatus for the vertical orientation cone calorimeter testing of flexible polyurethane foams. *Fire Mater*. 2015;40:158-176.
32. Knapp GM. The Analysis of the Transition from Smoldering to Flaming in Polyurethane Containing Assemblies Representative of Upholstered Furniture [Master of Science thesis]. University of Maryland, 2019. <https://drum.lib.umd.edu/handle/1903/25190>. Accessed April 14, 2020.
33. Blais MS, Carpenter K, Fernandez K. Comparative room burn study of furnished rooms from the United Kingdom, France and the United States. *Fire Technol*. 2019;56:489-514.
34. Denize HR. *The Combustion Behaviour of Upholstered Furniture in New Zealand*. Christchurch, New Zealand: University of Canterbury; 2000.
35. "Fire Hazard Comparison of Fire-Retarded and Non-Fire-Retarded Products" Babrauskas, V.; Harris, Jr., R. H.; Gann, R. G.; Levin, B. C.; Lee, B. T.; Peacock, R. D.; Paabo, M.; Twilley, W.; Yoklavich, M. F.; Clark, H. M. NBS Special Publication 749, National Bureau of Standards, Gaithersburg, MD, 1988. <https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nbsspecialpublication749.pdf>. Accessed April 14, 2020.

How to cite this article: Morgan AB, Knapp G, Stolarov SI, Levchik SV. Studying smoldering to flaming transition in polyurethane furniture subassemblies: Effects of fabrics, flame retardants, and material type. *Fire and Materials*. 2021;45: 56-67. <https://doi.org/10.1002/fam.2847>