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Evaluating fire blocking performance of barrier fabrics

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SUMMARY

A series of evaluations were performed on different types of barrier fabrics (BFs) used in soft furnishings. Fundamental properties that influence the heat transfer characteristics of barrier material as it relates to thermal protection of cushioning components in upholstered products are discussed. This is important to enable a priori selection of BFs such that a final upholstered product complies with flammability regulations.

Heat transfer measurements are used to determine effectiveness of materials to be used as barrier materials. A new bench-scale composite test method is also described to assess qualitative fire blocking performance of BFs. When tested for heat transfer characteristics, the area density and thickness of BFs show strong influence. However, when tested as a composite in a mock-up assembly, the BFs considered in this study showed a clear distinction between active and passive BFs. In the case of chemically active BFs, the construction parameters and material properties such as thickness, air permeability, and heat transfer were of little significance. In the case of passive BFs, however, these parameters became decisive. Results from this study suggest that if the BF is not an active fire barrier, then the amount of heat transferred through BF is critical. Copyright © 2013 John Wiley & Sons, Ltd.

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KEY WORDS: barrier fabrics; soft furnishings; upholstered furniture; mattress; flammability; smoldering ignition; thermal protective performance; heat release rate; thermal degradation

1. INTRODUCTION

The federal flammability regulation (16 CFR Part 1633 [1]) for residential mattresses, enacted in 2007 by the Consumer Product Safety Commission (CPSC), has generated much interest in understanding the burning behavior of mattresses as well as in developing new materials for mattress construction. To comply with this open flame regulation, the mattress manufacturers are predominantly using fire blocking barrier materials. Currently, there is no federal flammability regulation for residential upholstered furniture, but CPSC has proposed a regulation (CPSC 16 CFR part 1634 [2]) that defines a smoldering and open flame metric for these products. One option to comply with the proposed 16 CFR Part 1634 is to incorporate a barrier material, also called barrier fabric (BF), that has passed smolder and open flame ignition tests into the residential upholstered furniture. Thus, BFs are expected to play an increasingly important role in reducing the fire hazard of soft furnishings.

Strategically placed between the cover fabric (known as ticking in case of a mattress) and the cushioning layer, the purpose of fire blocking BFs is to reduce the flammability of soft furnishings by preventing or delaying direct flame impingement from open flames and/or heat transfer from smoldering ignition source to the more flammable core cushioning components. There are a significant number of commercial fire blocking technologies available in order to accommodate the

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vast requirements of the consumers, manufacturers, and regulatory agencies. In order to accomplish comprehensive understanding of the BFs available in the market and their performance attributes required to comply with the current 16 CFR 1633 regulation, NIST reviewed [3] several fire blocking technologies, their effectiveness, and potential test methods for characterizing barrier performance. The review [3] discusses various fire blocking technologies with respect to material type, fiber content, and fire blocking mechanisms. The review suggested that successfully achieving the desired level of fire protection requires appropriate matching of the barrier material to the desired characteristics of the soft furnishing. Moreover, very little is known about fire performance requirements of these barrier materials that are critical to comply with full-scale fire regulations for mattresses and upholstered furniture, which makes a priori selection of fire barrier materials difficult. Selection of BFs is therefore a process of trial and error with current test methods based on pass/fail criteria that do not quantify barrier effectiveness in terms of heat transfer or their ability to extinguish and/or lower the temperature of flames. Current test methods for barrier materials have been recently reviewed [4] and are based primarily on pass/fail criteria for a mock-up assembly as opposed to quantification of an individual component.

In the present work, fundamental BF properties that influence the heat transfer properties (HTP) as they relate to thermal protection of cushioning components in upholstered products are discussed. Heat transfer characteristics of BFs exposed to combined radiant and convective heat flux are studied and reported for the first time. Similar studies by Shalev and Barker [5, 6] on heat transfer characteristics of protective clothing have been previously reported wherein heat transfer measurements were utilized to estimate the amount of time required to cause second degree burns on human skin. There are clear similarities between the use of fabrics to protect human skin from high temperature sources and the use of BF to protect soft fillings in upholstered furniture from an external fire. However, in the case of upholstered furniture, the goal is to prevent or limit the contribution of the filling material to the overall heat release rate (HRR) of the fire. In practice, this requires limiting the amount of filling that is pyrolyzed to generate potential fuel and/or limiting the burning of released pyrolyzate. Pyrolysis of organic materials is generally an endothermic process requiring the addition of heat. Thus, the ability of a BF to reduce heat transfer to the filling is an important consideration. This suggests that one measure of the effectiveness of a BF is the amount of heat transferred through the material.

Besides heat transfer measurements, flammability test methods that characterize ignitability and HRR properties of BFs are also discussed. Cone calorimeter experiments were performed to distinguish between BFs with respect to ignition times, peak heat release rate (PHRR), total heat released (THR), and char yield. The time to ignition (TTI) relates to how quickly a BF can ignite if the ticking or cover fabric catches fire. The PHRR is related to the maximum heat released by the burning BF that maintains the fire because of a positive feedback mechanism involved in the burning process while the THR reflects the total amount of flammable content of the BF specimen. The char yield, both qualitative and quantitative, reflects the thermal protective property of the BF after it has been consumed in the fire. Thus, important information with regards to evaluating BFs can be obtained from cone calorimetry data.

A new bench-scale composite test method is also described to assess qualitative fire blocking performance of BFs. Bench-scale laboratory tests for individual components are suitable for screening new materials. However, these component tests cannot characterize the fire hazard posed by upholstered composites, and hence, composite flammability tests are essential to measure the fire performance under end-use conditions. Moreover, the flammability of upholstered products can be drastically impacted by the structure of BFs and of the finished product, and other factors, which may mean that it is not possible to predict the full-scale behavior of the BFs without testing them in the context that defines the final product. In addition, BFs could fail because of stress-induced separation/splitting that results in exposing the cushioning materials of the soft furnishing to high temperatures and flames. When exposed to heat and/or flames, BFs undergo chemical and/or physical changes (e.g., dissipation of heat, release of flame retardant (FR), and formation of a protective char), and these may cause the BF to shrink, become stiff and/or brittle, and/or become thinner. In an attempt to better understand the burning behavior of composite assemblies and for assessing fire performance of barrier materials, a bench-scale composite test has been developed. Finally, general principles for engineering and evaluating the effectiveness of BFs are provided.

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2. EXPERIMENTAL

2.1. Materials[‡]

The experimental matrix covers the most extensively used fibers and fiber blends in the BF industry [3]. These include boric acid treated cotton, FR rayon, FR polyester, glass fiber, carbon fiber, and blends thereof. The exact fiber blend compositions are proprietary and thus were not available. BFs made from the latest core-yarn technology and high-performing carbon fibers (oxidized polyacrylonitrile fibers) were included.

The types of BFs used in soft furnishings are mainly influenced by end user applications and cost. Most commonly, highloft, nonwoven fiber battings are used in residential mattress applications, whereas coated or laminated textiles are more common in institutional and residential upholstered furnishing applications [3]. BFs constructed from inherently fire resistant fibers[§] are frequently used in high-performance applications (e.g., aircraft seating, seating in other mass transport vehicles, and public buildings). The range is indicated by list of commercially available BFs included in this study given in Table I. The list includes a variety of textile structures including highloft, nonwoven battings, knitted, and woven structures used in a variety of applications. With such a varied selection of BFs, it was possible to identify the factors to which the HTP were related most significantly. The BFs varied in average thicknesses from 0.1 to 7.8 mm.

Depending on the mode of fire blocking technology employed, the BFs in Table I are identified as active or passive. Active BFs have a chemical effect on the fire. The chemical activity of active BFs can be in the condensed phase through enhanced char formation (e.g., BF-1, BF-2, BF-3, BF-4, BF-5), gas phase via flame quenching and/or intumescence (e.g., BF-10, BF-11, BF-12, BF-15), or both. For the purpose of this work, only the BFs that can extinguish the flames and prevent the outer upholstery from burning are classified as active BFs in Table I. Passive fire barriers (BF-1, BF-2, BF-3, BF-4, BF-5, BF-6, BF-7, BF-8, BF-9, BF-13, BF-14, BF-16, BF-17, BF-18, BF-19) prevent or delay the ignition of interior cushioning materials; however, they do not prevent burning of the outer upholstery. Their effectiveness derives from serving as a physical and/or thermal barrier between some or all of the fuel and the potential ignition source.

Barrier fabrics can also be distinguished as thermally thick or thermally thin materials. A material is considered to be thermally thick if the heat penetration depth is less than the physical depth [7]. In thermally thin materials, heat absorbed on one surface of the material penetrates its thickness sufficiently rapidly, so there is no significant temperature gradient through the material's depth [8].

2.2. Test methods

2.2.1. Heat transfer. A thermal protective performance (TPP) instrument developed by Measurement Technology Northwest was used, for the first time, to quantify the heat transfer characteristics of BFs. A schematic of the TPP test apparatus is shown in Figure 1. It consists of two propane fueled Meeker burners and a bank of nine quartz radiant heating elements calibrated to provide 50% convective and 50% radiative heat flux. The Meeker burners were tilted at an angle of 45° from the horizontal (Figure 1) so that the flames converged at a point immediately under the test specimen. The propane burner flames were visually monitored to avoid any turbulence. The specimens were exposed to a total heat flux of $65 \pm 5\,\mathrm{kW/m^2}$ for 70 s. This exposure condition represents the maximum heat flux that a mattress top experiences during a full-scale open flame test [9, 10] as described in 16 CFR part 1633 [1]. The total heat flux was calibrated every day prior to experimentation.

The sample carriage consists of a frame for securing the BF specimen and a heat sensor placed in direct contact with the back of the BF. The heat sensor is a slug calorimeter embedded in an insulating board that is placed face down on the fabric assembly. The slug calorimeter consists of a

[‡]Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology nor is it intended to imply that the materials or equipment identified are necessarily the best available for this purpose.

[§]Fire resistant fibers self-extinguish upon removal of the ignition source, thus preventing flame spread, whereas flame retarded fibers burn slowly because of a flame retarding mechanism.

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Table I. Description of BFs used in soft furnishings. Uncertainties are reported as Type A uncertainties [23,22] with experimental standard deviations.

Sample	Fiber blend	Structure	Area density§, g/m^2	Average thickness, mm	Type of BF
BF-1	FR rayon/polyester	Thermally bonded highloft	155	4.1 ± 0.1	Passive
BF-2	FR rayon/polyester	Thermally bonded highloft	230	6.7 ± 0.2	Passive
BF-3	FR rayon/polyester	Needle punched	240	7.8 ± 0.6	Passive
BF-4	Boric acid treated cotton/FR rayon/polyester	Needle punched/stratified	230	5.7 ± 0.1	Passive
BF-5	Boric acid treated cotton	Needle punched	230	6.9 ± 0.8	Passive
BF-6	Carbon fiber	Nonwoven felt	500	3.9 ± 0.2	Passive
BF-7	Carbon fiber	Nonwoven felt	576	7.2 ± 0.1	Passive
BF-8	FR rayon/polyester	Needlepunched	237	4.3 ± 0.1	Passive
BF-9	FR rayon/polyester	Needlepunched	240	2.2 ± 0.1	Passive
BF-10	FR polyester/FR rayon	Stitchbond	165	0.7 ± 0.1	Active
BF-11	Glass fiber core/FR acrylic fiber	Knit barrier using core-yarn technology	186	0.9 ± 0.1	Active
BF-12	Glass fiber core/FR acrylic fiber	Knit barrier	237	1.6 ± 0.1	Active
BF-13	FR rayon/glass fiber/PLA fiber	Knit barrier	165	1.4 ± 0.1	Passive
BF-14	Carbon fiber	Circular knit	250	1.2 ± 0.1	Passive
BF-15	Glass fiber core/FR acrylic fiber	Woven barrier	170	0.5 ± 0.1	Active
BF-16	FR rayon/crystalline silica fiber/PLA fiber	Nonwoven	290	2.9 ± 0.1	Passive
BF-17	Glass fiber	Woven barrier	150	0.2 ± 0.1	Passive
BF-18	Glass fiber	Woven barrier	170	0.1 ± 0.1	Passive
BF-19	Glass fiber	Woven barrier	320	0.3 ± 0.1	Passive

Note: BF, barrier fabric; FR, flame retardant; PLA, poly lactic acid.

§For textile materials, density is generally expressed as mass per unit area. The standard uncertainty (Type B) [23, 24] in measuring area density is about ±5 g/m2. A Type B evaluation of standard uncertainty is based on scientific judgment using experience with, and general knowledge of, the behavior and property of relevant materials and instruments.

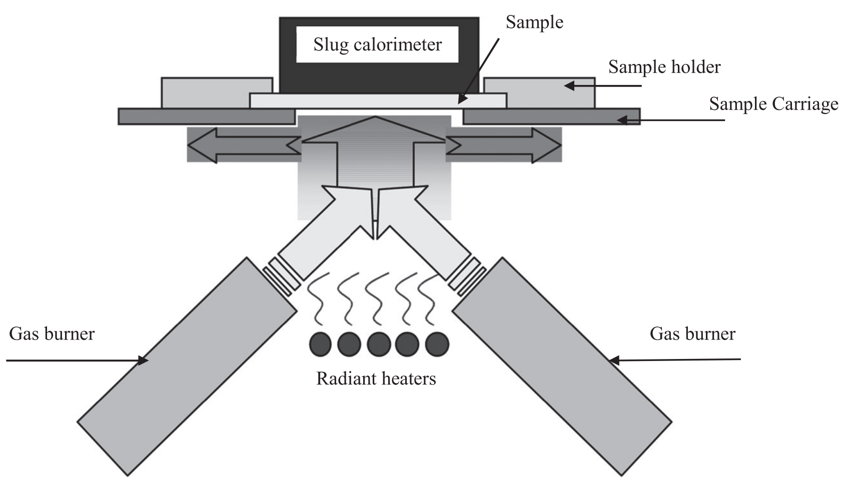

Figure 1. Schematic of thermal protective performance testing device.

blackened copper disk 40 mm in diameter with a thickness of 1.6 mm. Three 32-gauge chromel/alumel thermocouples are mounted in the disk at 120° intervals. The heat flux sensor with calibrated slug calorimeter is connected to a data acquisition system that records the rise in temperature of the sensors as a function of time. Thermocouples secured in the copper slug calorimeter, which is in

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direct contact with the back surface of the specimen, measure the rise in temperature. The rates of temperature rise or the slope of the temperature versus time trace are used in conjunction with the calorimeter constants provided by the manufacturer to compute the heat flux received. The water-cooled shutter is pneumatically actuated and automated for precise control of exposure timing. It covers the heating elements to allow time for the sample carriage to move into position above the heat source. At the start of the test, the heat sensors are approximately at room temperature. The rise in temperature after exposure is calculated by subtracting the starting temperature from the recorded temperature. A particularly useful feature of this test procedure is a continuous calorimetric trace useful for analyzing the fabric heat transfer characteristics.

Barrier fabric materials were placed on the sample holder in the same configuration used in full-scale open flame flammability testing of a residential mattress, in that the ticking (fabric over the BF) is exposed to the heating elements and the BF is in contact with the sensor. This condition measures the protective characteristics of the total assembly. The ticking material used in this study was a stitchbond fabric containing 69% rayon and 31% FR polyester blend and was kept consistent in all composite specimens. Such a ticking material was chosen to avoid any melt-dripping of ticking and/or BFs, thereby damaging the quartz tubes. The use of a FR ticking, however, is not expected to interfere with measurements of the HTP of BFs.

Upon completion of the test, the slug calorimeter was carefully examined for any sticky residue or char from the degraded BF. Although prior studies have shown that the state of the copper surface has little influence on the measurement of heat transfer through textile materials [11], any accumulated residue was carefully cleaned from the sensor and sample holder surfaces.

2.2.2. Cone calorimetry. The cone calorimeter was operated according to the procedures provided in ISO 5660–1 [12]. The sample was located 2.5 cm below the base of the cone. Most textile materials are thermally thin materials and have very high air-to-fiber ratio. This characteristic feature of textile materials makes it very difficult to maintain their configuration. Such materials often curl, melt, and char when exposed to high incident heat fluxes. The changing specimen configuration complicates interpretation of the experimental results. In order to limit configuration changes in materials and improve measurement reproducibility, the specimen assembly [13] shown in Figure 2 was used. Pieces of ceramic blanket of various thicknesses were utilized to ensure that barriers were located at the proper height below the cone calorimeter. While it is recognized that the type of backing materials can influence cone calorimetric data [14], it is important to note that cone calorimeter experiments in this study were performed to distinguish between BFs with respect to ignition times, PHRR, THR, and char yield. For these purposes, it is sufficient to test materials over a common insulation and under a common irradiance [15].

An incident heat flux of 50 kW/m^2 was judiciously selected: (i) because it represents a developing fire more than a fully developed fire at 65 kW/m^2 [16]; (ii) this flux represents the immediate reaction-to-fire when the BF is exposed to the burners in a full-scale mattress flammability test described in 16 CFR 1633 [1]; and (iii) because the BFs are expected to be fire resistant and/or flame resistant materials, ignition of such materials at incident heat fluxes below 50 kW/m^2 were not expected.

2.2.3. Composite test. A modified 'Mydrin test' [17] was chosen as the bench-scale test for the BFs. The Mydrin test was originally developed [18] as a simplified version of a Source 1 ignition condition in British Standard BS5852: 1979 [19]. Its purpose was to assess the flammability performance of FR

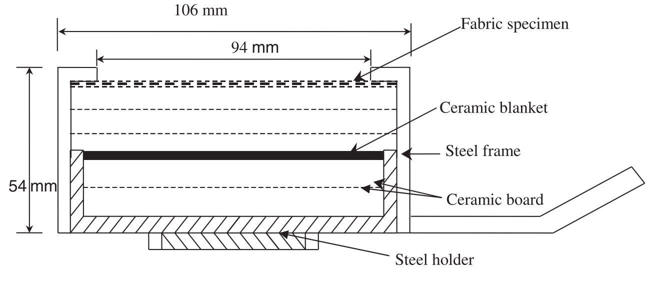

Figure 2. Specimen assembly for cone calorimetry experiments.

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cover fabrics used in upholstered furnishings. The test was considered to be an acceptable mock-up test that inexpensively and accurately indicate the ignition behavior of full-scale products of complex structures when tested in accordance with BS5852 [17]. The test setup is shown in Figure 3. A premixed butane gas burner was used with a flame height adjusted to 40 mm as specified in BS 5438 [21]. The flame was applied to the face of the composite for 20 s and then removed. If the composite continued to flame and/or smoke for more than 2 min and/or, heat or afterglow for more than 15 min after removal of the ignition source, a 'fail' was recorded for the test; otherwise, a 'pass' was reported. This test criterion, however, was limited to mock-up composites using FR cover fabrics. Because BFs were used in this study, the Mydrin test was modified as described later.

The new bench-scale composite test developed for this study included a new specimen configuration including a piece of polyurethane foam (PUF) (average density of 28.4 kg/m^3 or 1.77 lb/ft^3, and average air permeability of 0.33 m^3/min or 11.7 ft^3/min) of approximately 220 mm × 150 mm × 22 mm dimensions as the flammable filling part of the composite to be tested. PUF samples were custom made according to NIST specifications in a small pilot plant by Foamex International Inc., PA (FXI). Manufacturing details and physical properties of PUF (formulation B12) are described in a previous report [19]. The BFs and the ticking were cut into pieces, approximately 264 mm × 194 mm and pinned onto the foam to form an upholstered composite. The BF was placed between the ticking and the PUF. The back side of the foam was not covered with BF and the ticking. The fire blocking performance of BFs was tested with and without the ticking. The ticking selected for this composite test was a woven fabric with acrylic backcoating and had a flame spread rate of 37 ± 3 mm/s in the vertical orientation when subjected to an open flame as defined in BS 5438 [20]. The ticking has an area density of approximately 200 g/m^2 with a fiber composition of 77% rayon and 23% polyester. This particular ticking is classified as Class B according to its smoldering performance as defined in 16 CFR part 1632.6 [22].

Figure 3. Vertical flammability test rig developed for the 'Mydrin' test.

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Initially, the composites were tested as an assembly of PUF/BF/Ticking. Composite samples, which showed self-extinguishing properties in the presence of a fairly flammable ticking, were not included in further testing. The PUF/BF/Ticking composite samples that burned extensively, primarily because of burning of ticking, were tested without tickings. Burning behavior was characterized in terms of duration of the flaming, thermal damage to the foam, and self-extinguishing behavior.

3. RESULTS AND DISCUSSION

3.1. Heat transfer properties of barrier fabrics

The heat transfer characteristics of BFs have been assessed using the TPP instrument described in Section 2.2.1. The average rise in temperature, the heat flux recorded at the unexposed surface of a BF, the total amount of heat energy transferred (THT) through the BF, and the maximum heat flux measured at the unexposed side of a BF during a 70 s exposure time are given in Table II. Uncertainties in measurement of various temperature and heat flux related parameters are reported as Type A uncertainties [23, 24] with experimental standard deviations in Table II. A Type A evaluation of standard uncertainty is determined by calculating standard deviation of the mean of a series of independent observations.

The increases in temperature of the unexposed surface as a function of time for thermally thin woven and knitted BFs are shown in Figure 4. BF-10 (a stitchbond material) is also included in this category of woven barrier materials because the physical characteristics are similar to those of woven materials. BF-10, BF-11, BF-12, BF-13, and BF-15 show instantaneous rises in temperature as opposed to BF-14, BF-17, BF-18, and BF-19, where rises in temperature at the unexposed surface are not seen until almost 20 s of exposure to the heat flux. The latter BFs have very low gas permeability and therefore very little, or no, heat transfer via convection. Heat transfer in these BFs is primarily by conduction and radiation. Moreover, conductive heat transfer is negligible under highly turbulent flaming conditions [5], thereby resulting in delays in temperature rise.

Figure 5 shows temperature-time curves for nonwoven BFs. Generally, all nonwoven, highloft BFs show lower heat transfer as compared to thermally thin, woven, and knitted BFs. Increases in temperature at the unexposed surfaces of thermally thick BFs are not seen until the BFs start decomposing. Thermally thin BFs show temperature rises up to 300°C during the 70 s exposure time, whereas maximum temperatures recorded at the unexposed surface of thermally thick BFs are all less than 225°C. For some BFs, the initial slopes of the temperature-time curves vary because the heat exposure produces fundamental changes in fabric thermal and spatial properties through mechanisms of pyrolysis, char formation, and shrinkage. This is particularly true in the case of highloft nonwoven BFs where the volume of air is larger than the volume of fiber.

Data were analyzed to determine the relationship between the heat transfer through BFs and BF characteristics such as fiber content, area density, and thickness. Figure 6 shows a plot of THT through the BF as a function of the area density of BF, and Figure 7 shows a plot of THT as a function of BF thickness. There is considerable scatter of data in the range of 150–300 g/m^2 in Figure 6, suggesting significant influence of fiber content. However, THT through the BF was approximately inversely related to its thickness (Figure 7).

Passive barrier materials BF-17, BF-18, and BF-19 have similar woven structures, fiber content, and thicknesses but different area densities. The amount of heat transferred and, hence, the TPP of these BFs containing inherently non-combustible glass fiber varies with the area density. The THT through BF-17 (area density = 150 g/m^2) was recorded as 43.3 ± 2 MJ/m^2, whereas BF-18 with higher area density (170 g/m^2) has a lower heat transfer rate, and the THT during the 70 s exposure was 30 ± 8 MJ/m^2. The amount of heat transferred through woven glass fiber fabrics decreased with increase in their area density. However, for BF-19 (320 g/m^2), a significantly higher heat transfer rate was recorded. The high heat transfer rate of BF-19 could have been due to higher thermal conductivity [25] of the densely woven glass fiber fabric. This suggests that there is a critical area density above which the additional benefit in thermal protection gained by the increase in area density is offset by the increased efficiency of thermal conduction.

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Table II. Heat transfer characteristics of BFs used in soft furnishings. Uncertainties are reported as Type A uncertainties [23, 24] with experimental standard deviations.

Sample specification	Average heating rate of heat sensors, °C/min	Maximum heat flux at unexposed side of barrier at 70 s, kW/m^2	Total amount of heat transferred, MJ/m^2	TPP, J/cm^2 (cal/cm^2)	HTF, J/g	Description of char
Thermally thick, nonwoven, highloft BFs						
BF-1	160 ± 30	13.1 ± 0.4	52.0 ± 1.4	75 ± 4 (18)	335	Very thin, fragile
BF-2	150 ± 18	9.3 ± 3.4	30.2 ± 17.5	113 ± 15 (27)	130	Thick, pliable
BF-3	115 ± 5	7.4 ± 0.9	28.5 ± 0.9	126 ± 7 (30)	121	Thick, flexible
BF-4	120 ± 5	5.9 ± 1.6	28.8 ± 6.8	113 ± 3 (27)	126	Thick, flexible char with no cracks or holes
BF-5	90 ± 5	5.2 ± 1.6	24.6 ± 3.2	151 ± 14 (36)	109	Several holes in the char
BF-6	100 ± 5	7.3 ± 0.4	26.0 ± 3.2	126 ± 8 (30)	52	Full thickness, flexible char with no cracks or holes
BF-7	50 ± 5	1.9 ± 0.6	4.6 ± 2.5	268 ± 3 (64)	9	Full thickness, flexible char with no cracks or holes
BF-8	140 ± 5	9.10 ± 0.3	43.4 ± 6.6	105 ± 3 (25)	181	Brittle char, little shrinkage and no hole formation
BF-9	150 ± 5	10.3 ± 0.9	30.4 ± 9.0	75 ± 1(18)	125	Brittle char, little shrinkage and no hole formation
BF-16	160 ± 5	11.0 ± 1.2	46.9 ± 7.9	92 ± 3 (22)	162	Brittle char, little shrinkage and no hole formation
Thermally thin, woven and knitted BFs						
BF-10	260 ± 5	16.0 ± 4.9	70.5 ± 18.8	38 ± 1 (9)	430	Thin, permeable char
BF-11	250 ± 5	20.5 ± 0.2	87.5 ± 2.5	38 ± 0.4 (9)	473	Thin, flexible, permeable char
BF-12	220 ± 5	11.5 ± 5.8	52.1 ± 11.8	46 ± 1 (11)	219	Thin, flexible, permeable char
BF-13	220 ± 5	16.8 ± 0.1	66.0 ± 0.8	54 ± 1 (13)	400	Thin, flexible, permeable char
BF-14	205 ± 5	12.9 ± 0.9	38.4 ± 7.4	63 ± 2 (15)	152	Thin, flexible, permeable char
BF-15	230 ± 5	17.9 ± 0.6	75.4 ± 6.8	38 ± 1 (9)	441	Thin, permeable char
BF-17	205 ± 5	10.9 ± 1.7	43.3 ± 2.0	59 ± 2 (14)	287	Thin, non-permeable char
BF-18	190 ± 5	11.6 ± 3.0	30.0 ± 8.0	67 ± 5 (16)	176	Thin, non-permeable char
BF-19	240 ± 5	16.7 ± 1.9	70.3 ± 4.3	54 ± 2 (13)	219	Thin, non-permeable char

Note: BF, barrier fabric; TPP, thermal protective performance; HTF, heat transfer factor.

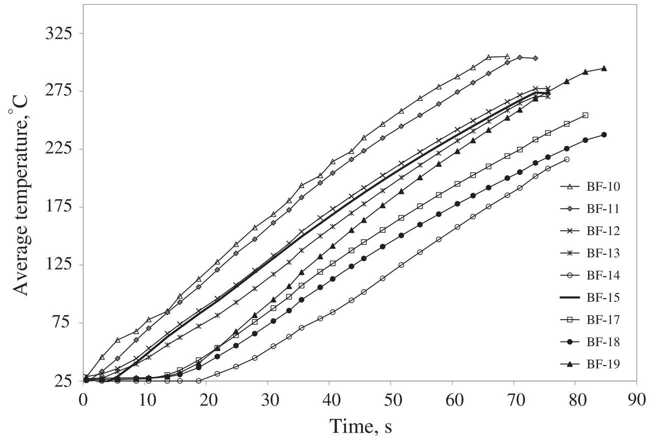

Figure 4. Thermal response of woven and knitted barrier fabrics (BFs).

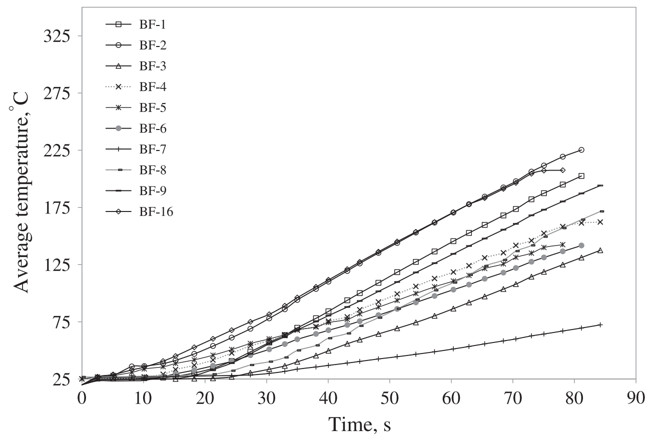

Figure 5. Thermal response of nonwoven barrier fabrics (BFs).

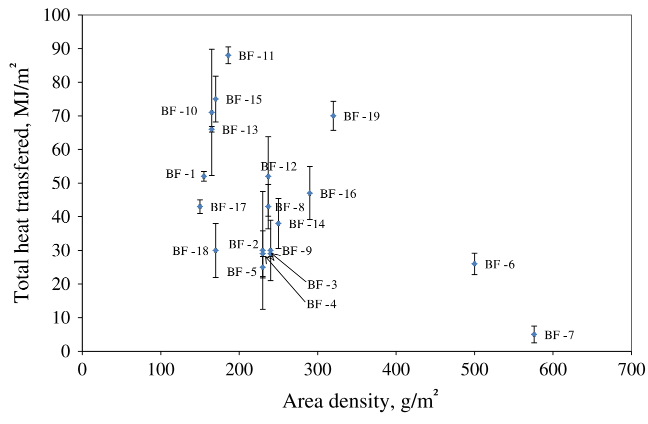

Figure 6. Correlation between total heat transferred and area density of the barrier fabrics (BFs). Uncertainties are reported as Type A uncertainties [21, 22] with experimental standard deviations.

BF-15 and BF-18 had similar area densities, fiber content, and woven construction. A lower amount of heat was transferred (30 ± 8 MJ/m^2) through BF-18, compared to BF-15, which was 75 ± 7 MJ/m^2. The higher heat transfer though BF-15 could be due to its higher porosity and hence higher

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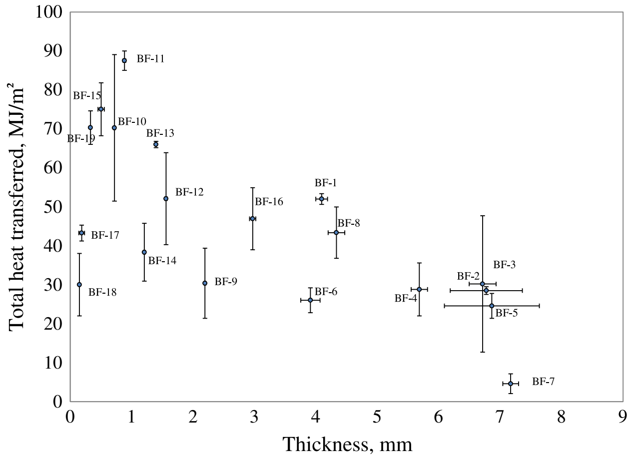

Figure 7. Correlation between total heat transferred and thickness of the barrier fabrics (BFs). Uncertainties are reported as Type A uncertainties [21, 22] with experimental standard deviations.

permeability of the woven structure. The woven BF-15 was more porous than the densely woven glass fiber fabric (BF-18). The pore size impacts the rate of air permeability, which in turn impacts the convective heat transfer.

Such a trend is also seen among the knitted BFs (e.g., BF-11, BF-12, BF-13, and BF-14). With similar fiber content in BF-11 and BF-12, BF-11 showed higher heat transfer rates. BF-12 has a higher area density (237 g/m^2) as compared to BF-11 thereby inhibiting convective heat transfer. Amongst the knitted BFs, BF-14 with inherently fire resistant carbon fibers and with the highest area density (270 g/m^2) has very low heat transfer rates. The THT value recorded for BF-14 was 38 ± 7 MJ/m^2.

Amongst the nonwoven BFs, BF-1 and BF-2 have similar fiber content and highloft construction. The difference in HTP of BF-1 and BF-2 is primarily because of the difference in their area densities and thickness. With a rise in temperature of about 150 ± 18°C/min at the unexposed surface of BF-2, the THT value is recorded as 30 ± 17 MJ/m^2. BF-1, however, has a higher heat transfer rate, and THT through BF-1 is recorded as 52 ± 1.4 MJ/m^2. The residual char of BF-2 was pliable as opposed to the thin fragile char of BF-1.

Fiber type can be an equally important characteristic in nonwoven highloft BFs effectiveness. Nonwovens BF-2, BF-5, and BF-7 have similar thicknesses but different area densities and are constructed from different fiber blends. BF-5 has boric acid treated cotton fiber and shows significant enhancement in HTP. The rise in temperature at the unexposed surface of BF-5 is 1.7 times slower (90°C/min) as compared to that for BF-2 (150°C/min). The higher heat transfer rate of BF-2 can be partly attributed to the high HRR of FR viscose/polyester blends. In BF-5, the boric acid catalyzes dehydration reactions of cotton fibers and facilitates char formation [26]. When exposed to an open flame, the boric acid decomposes endothermically to release water and cool the flame [27]. The main drawback of BF-5 is that the residual char had several holes in it, and this can have detrimental effects on the barrier effectiveness of a material. BF-7 is a nonwoven felt with the highest area density (576 g/m^2) and thickness (7 mm), and therefore lowest heat transfer rate, amongst all the BFs tested in this study. Moreover, the carbon fiber in BF-7 is inherently fire resistant and shows no signs of decomposition when exposed to a high heat flux of 65 kW/m^2. Compared to BF-7, a 43% thinner carbon fiber felt (BF-6, 4 mm thick) had 5 times higher heat transfer (26.0 ± 2.5 MJ/m^2) suggesting a strong correlation between thickness and THT for BFs with similar characteristics (e.g., construction and fiber type). It is important to note here that the area densities of BF-6 and BF-7 are somewhat comparable.

The heat transfer characteristics of barrier materials depend on their thermal conductivity, density, thickness, and thermal emissivity. In this study, thermal conductivity and thermal emission properties of barrier materials were not measured. However, the area density and thickness of BFs showed a strong influence on HTP. Thicker barrier materials with temperature gradients behaved as

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thermally thick barriers and resulted in lower heat transfer rates, whereas thermally thin barriers with constant temperatures throughout the depth of the material resulted in higher heat transfer rates. Thus, for better barrier effectiveness, the material should have sufficient thermal thickness.

In addition to BF thickness, density, and construction, other factors that influence heat transfer includes thermal conductivity and heat capacity of fibers, the nature of the boundary layer formed at the fabric air interface, the extent of endothermic reactions occurring in the solid or vapor phase, combustion products formed, and their thermal properties [6]. The mechanism of heat transfer through BFs comprises a more complex combination of absorption and reradiation, conduction, and perhaps forced convection. Surface transfer coefficients and surface optical properties affect, respectively, the convective and radiative heat transfer to the surface of the fabric. The process of heat transfer through the fabric is also affected by bulk heat capacity, bulk conductivity, fiber-to-air ratio, and air void distribution. It is therefore more meaningful to rank BFs using protective index. Reported in Table II are the BF weight normalized THT value, termed as heat transfer factor (HTF) having units of J/g. HTF is the ratio of the THT value to the fabric area density in g/m^2. The inverse of HTF can be arbitrarily defined as the thermal protective index (TPI) of BF. The ranking of BFs using protective indices is shown in Figure 8. Depending on the thermal thickness and fiber content, different BF types yielded different TPI values. The higher the TPI value, the better is the TPP of a BF.

3.2. *Flammability of fire barrier materials*

Various parameters derived from the cone calorimeter data including ignition times, PHRR, time to peak heat released (TTP), THR, fire growth rate (FIGRA) indices, and char yield are given in Table III for the various BFs. All the BFs had relatively short TTI values, but self-extinguished quickly (flame out (FO) time ≤ 50 s), have low PHRR, low TTP, and low THR values. The residual char after combustion was measured, and most BFs had at least 40% of their original mass retained. Moreover, experimental times for such materials are relatively short where burning takes place at a high rate before the sample self-extinguishes.

Numerous researchers, for example,[13,16,28, 29], have shown that cone calorimeter measurements on materials such as those considered in the current study can provide significant experimental challenges associated with the materials' low mass, thickness, and burning behavior. Various approaches for improving the reliability and reproducibility of the measurements have been discussed. These same sample properties often lead to periods of heat release in typical cone calorimeter experiments that last on the order of seconds or tens of seconds. Such heat release times are comparable to the response times of most cone calorimeters, with a value of close to 6 s being typical. Recorded HRRs are known to be distorted from the actual time behavior when rapid changes take place over periods comparable to the response time. For the sharp peaks characteristic of these experiments, measured values of maximum HRR would be expected to underestimate the actual value, while the time required to reach the maximum value would be overestimated.

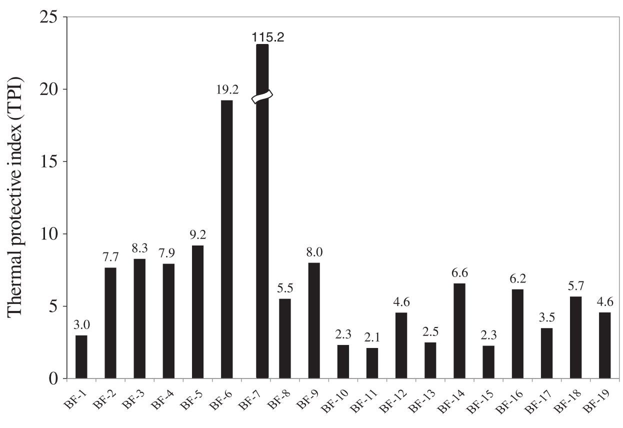

Figure 8. Ranking of barrier fabrics (BFs) using thermal protective indices.

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Table III. Flammability properties of BFs under fully ventilated conditions in the cone calorimeter. Uncertainties are reported as Type A uncertainties [23, 24] with experimental standard deviations.

Sample	TTI, s	FO, s	PHRR, kW/m^2	TTP, s	FIGRA, kW/s	Char yield, %	THR, kJ
BF-1	6	24	134 ± 11	10	13.4	40	19 ± 4.0
BF-2	4	50	137 ± 3	6	22.8	39	43 ± 0.7
BF-3	4	34	104 ± 4	7	14.8	42	31 ± 2.6
BF-4	5	33	108 ± 4	8	13.5	37	35 ± 2.3
BF-5	6	35	108 ± 6	8	13.5	38	44 ± 5.2
BF-6	11	36	6 ± 1	8	0.8	68	32 ± 3.3
BF-7	-	-	-	-	-	-	-
BF-8	6	28	22 ± 1	13	1.7	21	41 ± 12
BF-9	6	30	143 ± 8	12	11.9	35	25 ± 1.6
BF-10	4	20	102 ± 8	11	9.3	42	17 ± 1.7
BF-11	8	10	74 ± 32	11	6.7	61	14 ± 3.2
BF-12	8	10	115 ± 3	12	9.6	58	23 ± 1.8
BF-13	7	12	141 ± 10	12	11.8	43	16 ± 0.9
BF-14	10	20	14 ± 1	14	1.0	46	40 ± 2.2
BF-15	7	10	7 ± 4	10	0.7	73	9 ± 3
BF-16	6	38	186 ± 20	12	15.5	43	27 ± 5.4
BF-17	-	-	-	-	-	-	-
BF-18	-	-	-	-	-	-	-
BF-19	8	10	6 ± 1	8	0.8	78	7 ± 0.8

Note: BF, barrier fabric; TTI, time to ignition; FO, flame out; PHRR, peak heat release rate; TTP, time to peak; FIGRA, fire growth rate; THR, total heat released.
-, not tested because of limited sample availability.

The sample holder system shown in Figure 2 was designed to minimize problems associated with testing fabrics and barrier materials. Even though approaches have been developed for correcting for time response effects [13,30–32], such corrections were judged to be beyond the scope of this work, and the following results are based on the experimental data as recorded. As a result, the findings represent relative characterizations of BFs and should not be considered as absolute values.

In general, the TTI data suggest that the physical thickness does not influence the TTI of BFs under a given set of conditions. TTI is higher for BFs containing inorganic fibers, for example, BF-6, BF-14, and BF-19. BFs BF-6, BF-14, BF-15, and BF-19 have small flaming period and very low PHRRs ($<$15 kW/m^2) due to the presence of inherently fire resistant fibers. BFs containing organic fibers (BF-1, BF-2, BF-3, BF-4, BF-5, BF-9, BF-10, BF-12, BF-13, and BF-16) burn with PHRR values in excess of 100 ± 10 kW/m^2 with the exception of BF-8. BF-8 has a very small PHRR value of 22 ± 1 kW/m^2. BF-8 is a blend of FR rayon/proprietary inorganic fiber/polyester and has higher area density (~240 g/m^2) with low thickness (4 mm). The proportion of inorganic fibers to the FR rayon fibers is proprietary, but the lower PHRR values suggest significant fraction of inorganic fibers in the blend. FIGRA values distinguish BFs containing inorganic fire resistant fibers (FIGRA $<$ 2 kW/s), BFs with active FRs (FIGRA $<$ 10 kW/s), and passive BFs (FIGRA $>$ 10 kW/s).

3.3. Burning behavior of composite assemblies

Digital images of composite assemblies that exhibited self-extinguishing behavior when exposed to a 40 mm butane flame for 20 s in a modified Mydrin tests are shown in Table IV. For all composites tested, the initial flame spread was tilted slightly from vertical because of the direction of air flow in the exhaust system. All the composite assemblies in Table IV had active BFs. As mentioned earlier, active BFs can not only help prevent the ignition of interior foam but can also prevent the outer upholstery, that is, ticking or cover fabric, from burning.

Although BF-10 has a relatively high heat transfer rate when exposed to combined radiant and convective heat fluxes (Table II), the composite sample with the BF-10 barrier self-extinguishes when exposed to the open flame ignition source for 20 s. Under forced burning conditions, as in cone calorimetry, BF-10 had a PHRR of 102 ± 8 kW/m^2 and the sample burned with a char yield of 42% (Table III). The active (vapor phase) FR mechanism is operational only when the FR sample is

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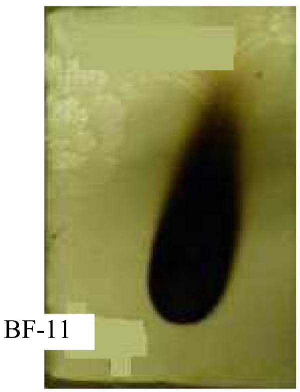
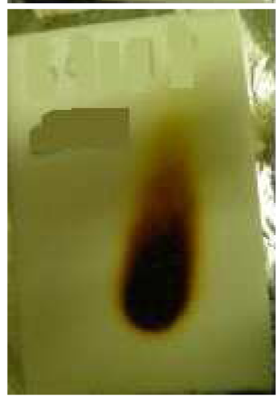
Table IV. Digital images of composite samples with active barrier fabrics (BFs) exposed to 40 mm butane flame for 20 s.

Sample	Full composite (PUF/BF/Ticking)	PUF/BF	PUF	Comments
BF-10				Self-extinguished after 30 s
BF-11				Self-extinguished in 40 s

(Continues)

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Table IV. (Continued)

Sample	Full composite (PUF/BF/Ticking)	PUF/BF	PUF	Comments
BF-12				Self-extinguished (as soon as flame was removed)
BF-15				Self-extinguished (as soon as flame was removed)

Note: BF, barrier fabric; PUF, physical unclonable function.

Table V. Digital images of composite samples with passive BFs exposed to 40 mm butane flame for 20 s.

	Full composite samples tested with ticking					Composite samples tested without ticking	
Sample	Full composite (PUF/BF/Ticking)	PUF/BF	PUF	Duration of flaming, min	Comments	PUF/BF	PUF
BF-1				2.3	Self-extinguished		
BF-2				3.5	Self-extinguished	Fail, foam catches fire	
BF-3				3.4	Self-extinguished	Not Tested (N/T)	

(Continues)

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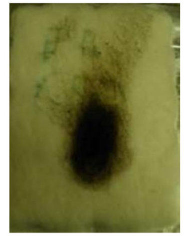
Table V. (Continued)

Sample	Full composite samples tested with ticking					Composite samples tested without ticking	
	Full composite (PUF/BF/Ticking)	PUF/BF	PUF	Duration of flaming, min	Comments	PUF/BF	PUF
BF-4	 BF-4			3.4	Self-extinguished		
						Self-extinguished as soon as flame was removed	
BF-5	 BF-5			3.3	Self-extinguished	N/T	
BF-6	 BF-6			4.0	Self-extinguished	N/T	

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BF-8				<4.0	Foam ignites	Self-extinguished as soon as flame was removed		
BF-9				4.5	Self-extinguished			
						Self-extinguished as soon as flame was removed		
BF-13				-	Foam ignites			

(Continues)

Table V. (Continued)

Sample	Full composite samples tested with ticking: Full composite (PUF/BF/Ticking)	PUF/BF	PUF	Duration of flaming, min	Comments	Composite samples tested without ticking: PUF/BF	PUF
BF-14				-	Foam ignites	Self-extinguished as soon as flame was removed 	
BF-16				-	Foam ignites	Self-extinguished as soon as flame was removed 	
BF-17				4.0	Self-extinguished	Self-extinguished as soon as flame was removed 	

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BF-18				4.0	Self-extinguished	Self-extinguished as soon as flame was removed  
BF-19				1.3	Self-extinguished	Self-extinguished as soon as flame was removed N/T

Note: BF, barrier fabric; PUF, physical unclonable function.

exposed to an open flame. BF-11 is a knitted barrier using corespun yarn with a glass fiber filament and sheath fibers of modacrylic made from acrylonitrile and vinylidene chloride. The modacrylic fiber contains an antimony catalyst as an additive. The sheath fiber imparts active flame retardancy to the BF. Despite being thermally thin with high air permeability, all active BFs (BF-10, BF-11, BF-12, and BF-15) acted as very good fire blocking fabrics when exposed to open flame ignition.

Digital images of composite samples with passive BFs exposed to a 40 mm butane flame for 20 s are shown in Table V. In general, these passive BFs prevent or delay the ignition of the interior foam; however, they do not prevent burning of the outer ticking or cover fabric. The duration of flaming for these composite assemblies is generally between 2 and 4 min. Those with longer durations of flaming were extinguished manually. Ignoring the edge effects, most of these BFs burn with the ticking and form a char in place. The extent of damage to the underlying foam primarily depends on the type and structure of the charred barrier material, which in turn depends on fiber content, structural attributes, and thickness of the BF. Composite assemblies tested with BF-5, BF-6, and BF-7 showed very little or no damage to the foam. Amongst the carbon fiber barrier materials, the knitted structure in BF-14 failed to protect the underlying foam. However, it can be noted from the images that the BF-14 failed mainly at the edges. The more porous structure of the knitted BF-14 failed to protect the foam at the edges. The heat transfer in the case of BF-14 is also much higher than for BF-6 and BF-7. Thus, it can be seen that if the BF is not an active fire barrier, then the amount of heat transfer through a barrier is critical, that is, the material should be thermally thick to protect the underlying foam. The extent of damage to the foam was much greater in the case of thermally thin barrier materials with no active FRs (e.g., BF-8, BF-9, BF-13, BF-16, BF-17, BF-18, and BF-19).

Digital images of PUF/BF composite assemblies tested without ticking are shown in Table V. The composite assemblies were exposed to a butane flame for 40 s, and the burning behavior was noted. In the absence of ticking, all PUF/BF composite assemblies exhibited self-extinguishing behavior. Depending on the type of BF, the extent of thermal damage to the PUF was evident from this experiment. Stratified BF-4 containing boric acid treated cotton and FR rayon performed best to protect the foam. Thermally thin, glass fiber containing barrier materials, for example, BF-17, BF-18, and BF-19 conducted greater heat to the PUF, and hence, there was more thermal damage to the foam, as seen in Table V. However, thermal degradation of the foam was not significant enough to be able to support combustion. The differences between the various BFs with regard to after-flaming time and char lengths were not considered to be particularly significant.

4. CONCLUSIONS

The purpose of a BF is to limit the cushioning material involvement in a fire by preventing and/or significantly delaying the ignition of core materials, lowering the HRR, reducing the rate of flame spread, and/or extinguishing the flames. BFs must limit the heat transfer into the interior foam via conduction, convection, and radiation.

This work has demonstrated that the modified TPP test method allows critical BF heat transfer characteristics to be monitored and provides fundamental insight into BF thermal response as it relates to thermal protection of cushioning components (e.g., PUF) in upholstered products. Thus, measurements of heat transfer rate in BFs are useful in assessing their effectiveness as fire barrier materials.

When tested for heat transfer characteristics, the area density and thickness of BFs have a strong influence. However, when tested as a composite in a mock-up assembly, the fire blocking barrier materials considered in this study showed a clear distinction between active and passive BFs. In the case of active BFs, the construction parameters and material properties such as thickness, air permeability, and heat transfer were of little significance. However, in the case of passive BFs, these parameters became decisive. Results from this study suggest that if the BF is not an active fire barrier, then the amount of heat transferred through BF is critical, that is, the material should be thermally thick to protect the underlying foam.

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Barrier fabrics used in soft furnishings are generally porous materials. The size of the pores defines the rate of air permeability, which in turn impacts the pyrolysis rate of materials within the barrier. The permeability should be low enough to prevent flaming combustion inside the BF, especially when pyrolysis gases accumulate underneath the barrier. Permeability of a BF before and after heat exposure should provide insight into changes in porosity and whether or not the material will act as an effective barrier to gas exchanges. The other important measurement that would give deeper understanding into how BFs degrade in a TPP test is the retention of bulk density after exposure. Changes in BF density reflect changes in thickness and weight caused by pyrolysis and shrinkage effects during heat exposure. Because density is a critical quantity in a transient heat transfer measurements, these changes would be of greater interest.

Barrier fabrics, when exposed to a fire, develop significant fire induced stresses and deformations, which should be properly accounted for in evaluating realistic response of barrier materials. Measurement of the breaking strength of BFs exposed to various heat fluxes may provide insight into the loss of tensile strength due to heat exposure.

The composite bench-scale test employed for this study is still in the developmental stage. The test method has its limitations with respect to sample size, edge effects, and orientation of the sample. Furthermore, PUF as a filling material has long shown high variability in such type of composite tests and requires extensive replication in order to obtain satisfactory results. Reproducibility and repeatability of the test therefore need to be addressed.

Because many factors can contribute to the capability of a given material to meet requirements of a BF, general principles for selecting BFs and engineering their fire safety need to be established. To engineer upholstered product safety, the BFs must be resistant to smoldering ignition sources as well as to open flames. Smoldering ignition studies of these BFs are currently in progress and will be the subject of a subsequent report. In developing further principles for engineering fire safety of BF, we propose two fundamental principles as important technical considerations. First, BF is protective in its function, and therefore, it must not become involved in burning during its protective function. Second, the BF must be instrumental in extinguishing flames from burning of cover fabrics or the tickings. Third, the BF must either provide adequate insulation to reduce heat transfer or have low permeability so as to limit rate of pyrolysis underneath the barrier.

With regards to test methods for evaluating BFs, both vertical flame test and methods based on heat release have proved insufficient. Ranking of BFs based on heat transfer measurements seems acceptable. Further study is required to look at longer duration exposures and to probe the mechanisms of degradative heat transfer. The material property data obtained in this study will be used to model the barrier effectiveness in end-use applications. Correlation between a bench-scale mock-up and large-scale, if not full-scale, product testing is also required and will be accomplished in the next phase of this study.

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