

NIST Technical Note 1728

**A Review of Fire Blocking
Technologies for Soft Furnishings**

Shonali Nazare
Rick D. Davis

November 2011

NIST Technical Note 1728

A Review of Fire Blocking Technologies for Soft Furnishings

Shonali Nazaré
Rick D. Davis

*Fire Research Division
Engineering Laboratory
National Institute of Standards and Technology*

November 2011



U.S. Department of Commerce
Rebecca M. Blank, Acting Secretary

National Institute of Standards and Technology
*Patrick D. Gallagher, Under Secretary of Commerce for Standards and
Technology and Director*

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept 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 entities, materials, or equipment are necessarily the best available for the purpose.

**National Institute of Standards and Technology Technical Note
Natl. Inst. Stand. Techn. Techn. Report 1728, 48 pages (November 2011)
CODEN: NTNUE2**

Abstract

Fire barrier fabrics (BFs) are expected to play an increasingly important role in complying with existing and proposed soft furnishing flammability regulations. Several fire blocking technologies have been explored to reduce the flammability of soft furnishings by preventing or delaying direct flame impingement and heat transfer from the flames or molten polymer to the core components. The number of commercial fire blocking technologies (e.g., woven and nonwoven fabrics, flame retardant coatings, and flame retardant polyurethane foam) is large in order to accommodate the vast requirements of the consumers, manufacturers, and regulatory agencies. Generally, highloft, nonwoven fiber battings are used in residential mattress applications, whereas coated or laminated textiles are more common in institutional and upholstered furnishing applications.

BF selection is generally a process of trial and error due to significant measurement science gaps. Successfully achieving the desired level of fire protection requires appropriate matching of the BF to the desired characteristics of the soft furnishing. In addition to a few examples that demonstrate the complexity that makes a priori selection of BFs difficult, various fire blocking technologies are discussed in this report with respect to material type, fiber content, and fire blocking mechanisms. Future trends in fire blocking materials are also briefly described.

In 2009, the National Institute of Science and Technology and American Fiber Manufacturers Association held a workshop on fire blocking barrier fabrics for soft furnishings. This manuscript discusses the past, present, and future state of the BF landscape based on knowledge obtained from the workshop and the subsequent knowledge gathered from literature and stakeholders. This review is the first part of a three manuscript series stemming from the workshop. The next two manuscripts will review mattress and upholstered furniture. The reviews will include discussions of construction, flammability testing, regulations, and the role of fire blocking barrier fabrics.

Keywords

Soft furnishings; upholstered furniture; barrier fabrics; mattress; flammability; review; regulations

This page left intentionally blank

Contents

Abstract	iv
List of Tables	vii
List of Figures	viii
List of Acronyms and Abbreviations	ix
1. Introduction	1
2. Soft Furnishings	1
2.1. Mattresses	3
2.2. Upholstered furniture.....	6
3. Fire Blocking Technologies for Soft Furnishings	7
3.1. Barrier fabric types	9
3.1.1. Woven BFs	9
3.1.2. FR coatings on woven BF or cover fabric	11
3.1.3. Composite BFs	12
3.1.4. Nonwoven BFs	12
3.2. Polymeric foams	14
4. Performance of Fire Barriers	15
4.1. Impact of BF on flammability of mattresses	15
4.2. Impact of BF on flammability of upholstered furniture	16
4.3. Performance assessment of BFs	18
5. Future Trends in Fire Blocking Technologies	22
6. References	33

List of Tables

Table 1. Examples of commercially available BF for soft furnishings.31

Table 2. Performance and properties of various cover fabrics in cigarette ignition and small open flame tests [42].31

Table 3. Performance of various BFs in cigarette ignition, small open flame, and wooden crib tests [42]. Not tested (grey), Pass (yellow), Failed (red), No ignition (X), Ignition (√).32

List of Figures

Figure 1. Schematic of a typical residential mattress and foundation set: (a) innerspring and (b) solid foam.	24
Figure 2. Examples of upholstered furniture: (a) stacking chair, (b) stacking chair with no cushioning on the back, (c) office chair, (d) fully upholstered chair, (e) lounge chair and (f) two-seat sofa or love seat.	25
Figure 3. Comparison of innerspring mattresses with different types of filling materials in the presence or absence of BF [29].	26
Figure 4. Impact of BF on Cal TB 133 test results [39].	26
Figure 5. Impact of different cover fabrics and fire barriers on PHRR of composite specimens tested under cone calorimeter (35 kW/m ²) [13].	27
Figure 6. Meeker burner testing set up for studying char characteristics.	27
Figure 7. Char characteristics of nonwoven felts. Note: Values in parentheses show exposure time to open flame.	28
Figure 8. Schematic of ASTM D 7140 test method for barrier materials.	28
Figure 9. Mockup arrangement for UFAC smoldering ignition testing of BFs used in upholstered furniture.	29
Figure 10. ASTM D 5238 test for smoldering ignition resistance of cotton batting: (a) start, (b) test in progress, and (c) end of the test. Cotton batting stack on left of (a) is placed on top of the cigarette/cotton batting stack on the right of (a) to form the testing setup in (b).	29
Figure 11. Modified Cal TB 117 for testing barrier flammability: (a) vertical and (b) horizontal configuration.	30
Figure 12. Schematic of TPP test device.	30

List of Acronyms and Abbreviations

ASTM	ASTM International
AFMA	American Fiber Manufacturers Association
BF	Barrier fabric
BHFTI	California Bureau of Electronic and Appliance Repair, Home Furnishings and Thermal Insulation
Cal TB	California Technical Bulletin
CFR	Code of Federal Regulation
CBUF	Combustion Behavior of Upholstered Furniture
CNF	Carbon nanofibers
CNF/BF	Carbon nanofiber coated barrier fabric
CNF/PUF	Carbon nanofiber coated standard polyurethane foam
CPSC	U.S. Consumer Product Safety Commission
DMTA	Dynamic mechanical thermal analyzer
EPD	Environmental Product Development
EHS	Environment, Health, and Safety
FAA	Federal Aviation Authority
FR	Flame retardant
FRD	Fire Research Division
HR	Heat release
HRR	Heat release rate
IR	Infrared
LbL	Layer-by-layer assembly/coating
LOI	Limiting oxygen index
MWCNT	Multi-walled carbon nanotubes
NIST	National Institute of Standards and Technology
PHRR	Peak heat release rate
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
PUF	Standard polyurethane foam
RUF	Residential Upholstered Furniture
TGA	Thermal gravimetric analysis
TMA	Thermo mechanical analyzer
TPP	Thermal protective performance
TPT	Thermal protective temperature
UF	Upholstered furniture
UFAC	Upholstered Furniture Action Council
THR	Total heat released

1. Introduction

The estimated annual societal cost of soft furnishing fires to the United States economy is \$5 billion [1,2,3,4]. Soft furnishings are defined as mattresses and residential upholstered furniture (RUF), including sofas and cushioned or upholstered chairs. Fires in which a soft furnishing product is the first item ignited accounts for 5 % of all residential fires annually, but are responsible for a disproportionately high fraction of fire losses (33 % of the civilian fatalities, 18% of civilian injuries, and 11 % of the property losses) [1, 2, 3, 4]. The goal of a number of current and proposed state and federal regulations is to reduce these fire losses. Recent regulatory approaches have included risk of ignition through reduced ignition propensity cigarettes, reducing fire spread through residential sprinklers, and reducing the inherent fire hazard of fuel sources through lower heat release (HR) mattresses.

Existing flammability regulations for soft furnishings mainly address upholstered chairs and mattresses. The approaches manufacturers have taken to comply with these regulations are fairly consistent. To comply with the California Bureau of Home Furnishings and Thermal Insulation (BHFTI) soft furnishings flammability regulations (e.g., Cal TB 129 [5] and Cal TB 603 [6] for mattresses and Cal TB 133 [7] for upholstered chairs), manufacturers use a combination of flame retardant (FR) foam, FR cover fabrics, and/or barrier fabrics (BFs). To comply with the U.S. Consumer Products Safety Commission's (CPSC) mattress flammability (open-flame) regulation 16 CFR Part 1633[8], however, manufacturers are using only BFs . There is no federal flammability regulation for RUF, but CPSC has proposed a regulation (CPSC 16 CFR Part 1634 [9]) that defines a smoldering and open flame metric for these products. To comply with the 1634 open flame ignition test, it is anticipated that BFs will be required for RUF. In addition, restrictions on flame retardants are increasing due to sustainability regulations [10,11]. Thus, BFs are expected to play an increasingly important role in reducing the fire hazard of soft furnishings.

For more than 30 years, the Fire Research Division at the National Institute of Standards and Technology (NIST) has conducted research that has significantly contributed to the current understanding of soft furnishing flammability and the development of current standardized testing tools and methods [12,13,14,15]. The results from mattress flammability experiments [16] were used by CPSC to establish the testing protocol and performance metrics for 16 CFR 1633. In 2009, in order to facilitate the development of cost-effective BFs, NIST began conducting research focused on developing validated tools that accurately measure BF performance, enabling the understanding of the association of BF attributes with fire blocking performance, and evaluating new fire blocking technologies. To kick-off this new research focus, NIST and the American Fiber Manufacturers Association (AMFA) sponsored a BF workshop with participants from manufacturing, government, and academic institutes. This review manuscript summarizes the landscape of BFs based on the knowledge gained from the workshop, extensive literature review, stakeholder collaborations, and research activities at NIST.

2. Soft Furnishings

Since an extensive review of research on soft furnishing flammability is concurrently in preparation [17], the details provided here are intended to provide the background context for

this review of BFs. The term “fire hazard” is intended to qualitatively refer to the impact on fire losses. A soft furnishing with high ignition and heat release propensity has a greater probability of resulting in a more severe fire (deaths, injuries, and property loss) than a soft furnishing with low ignition propensity and low heat release properties. It would, therefore, be considered a greater fire hazard.

A large variety of soft furnishings can be found in the marketplace, stemming from the wide variety of customer needs for functionality, aesthetics, and affordability. To meet these needs, manufacturers use a range of textile materials, including woven fabrics, knitted fabrics, and non-woven highloft battings. These materials are based on various polymers, such as polyolefin, polyesters, cellulose, and their blends, and construction types, including plain weave, jacquard weave, and velour. Upholstered products are available in a wide range of geometries, frame and support materials, and physical construction types. In addition, the production of soft furnishing components and the process of upholstery can create variations. It is not well understood to what extent any of these variations impact the fire hazard of soft furnishings. NIST is currently conducting research to address these knowledge gaps [18].

Even though the function, construction, geometry, and materials used in soft furnishings differ, there are a few general similarities with respect to their flammability. For example, all soft furnishing products have a supporting frame, cushioning layers, and an outer covering fabric; each of which is generally flammable to some extent. Chemistry has a strong influence on the flammability behavior of a given component. For example, upon exposure to an ignition source, the outer covering fabric could ignite, char, or melt. The formation of a smoldering char may cause localized heating of the underlying components, resulting in thermal degradation of the foam and the release of volatile gases. These volatiles can ignite and support sustained flaming until all the combustible materials have been consumed. Flammability processes can be improved by preventing or delaying the ignition process using a technology that prevents thermal penetration (e.g., BF) or more thermally stable cushioning material. A melting covering fabric is another potential alternative to prevent ignition if the melting fabric self-extinguishes as it shrinks away from the ignition source. This requires a low HR with no other easily ignitable materials on the surface. This route can be desirable to manufacturers since many lower cost fabrics have this ‘melt-shrinking’ characteristic. Since this type of covering fabric provides resistance against smoldering ignition but not against open flame, other fire retarding technology will be necessary (e.g., BFs and/or FR foam).

The fabric design and construction can also impact the flammability of soft furnishings. For jacquard woven fabrics, the design can affect the peak heat release rate (PHRR) even if the basic yarn composition within the fabric remains unchanged. For example, design patterns with large motifs may have different burning characteristics than those with small motifs [19]. This is extremely important as the PHRR is often a critical performance metric for soft furnishing standards/regulations. One of the approaches to prevent heat transfer through the fabric (to the highly flammable foam core) is to use “pile” fabric structure that have raised fibers on the base fabric. Ignition of pile fibers creates what is called “surface flashing”, which is a very rapid spread of flames across the surface of the soft furnishing due to the easy ignitability and rapid consumption of these fibers. With low heat generating fibers, the flame spreads rapidly and

consumes the raised fibers without igniting the base fabric. Pile or velvet fabrics are examples of such materials commonly used in RUF.

Although a flexible polyurethane foam (PUF) core is common in both mattresses and RUF; other filling materials are also quite popular (e.g., cotton battings, polyester fiber battings, expanded polystyrene beads, feathers, and downs (fine feathers)) [20]. Compliance with flammability regulations is often achieved by preventing PUF from being exposed to heat and/or flame, as the fire hazard can significantly increase once PUF is ignited [14]. The flammability and flame retardancy of PUF has been well studied and widely reported [21,22,23,24]. However, there is still a lack of fundamental understanding of the relation between PUF attributes (e.g., surface area, air permeability, etc.), the manufacturing process (e.g., catalyst type and concentration), and PUF flammability (in both smoldering and open-flame performance). Knowledge gaps also include the flammability of other fill materials used in modern furniture. Loose-fill materials such as shredded PUF, "slickened" polyester fiber, and expanded polyurethane beads could be even more flammable than the typical PUF. NIST is currently conducting research to address these knowledge gaps [17].

Mattresses and RUF represent distinctly different fire threats due to variations in their construction geometries and usage. The United States residential fire fatality statistics are dominated by these two product categories of soft furnishings, which are separately discussed below.

2.1. Mattresses

A mattress set essentially consists of three main components: a frame, foundation and mattress (Figure 1). Mattresses are classified by the support system, which can be an innerspring, as in Figure 1(a), solid PUF as in Figure 1 (b), cotton batting, air or water. Innerspring mattresses account for nearly 80 % of the market. A typical innerspring mattress (Figure 1(a)) is covered by a comfort layer on one side for single-sided mattresses or on both sides for double-sided mattresses. The comfort layer is divided into three sub categories: cushioning layer, insulator and quilt. The quilt is the top layer of the mattress and is constructed of the ticking (the outer cover fabric of a mattress) and a low density PUF or fiber batting laminated or stitched to the underside of the ticking. The insulator and the cushioning layers may be stacked in varying sequences between the quilt and the innerspring support. The insulating layer is often a light-weight, low density nonwoven batting (or layers of nonwoven fabrics), whereas the cushioning layer may include flat or convoluted PUF, shredded pads of compressed polyester, or fiber battings.

Mattresses have a simple rectangular geometry and are available in well defined sizes: Twin (97 cm x 188 cm (38 in x 74 in)), Full (135 cm x 188 cm (53 in x 74 in)), Queen (152 cm x 203 cm (60 in x 80 in)), King (193 cm x 203 cm (76 in x 80 in)) and California King (183 cm x 213 cm (72 in x 84 in)). Construction and geometries of the mattress and foundation could be major factors affecting the fire performance of a mattress set. For this reason mattresses are tested (and sold) as a set (mattress and foundation). Mismatched geometries can have a small gap between the frame and the foundation, or between the mattress and the foundation. These gaps have been shown to result in accelerated burning, as small flames can travel through these gaps to reach the

underside of the mattress and/or foundation [25]. Due to this potential risk, fire protection is required for the foundation and the bottom of a single sided mattress as well as the top of the mattress in order to comply with mattress flammability regulations.

Test Standards

All residential mattresses sold in the U.S. are required to comply with the flammability performance metrics defined in 16 CFR 1632 [26] (smoldering ignition source) and 16 CFR 1633 (open-flame ignition source) [8]. Testing and failure criteria for the open flame regulation were based on the research conducted at NIST [16,27] and California Technical Bulletin 603 (TB 603). The 16 CFR 1633 test represents a situation in which the bedclothes have ignited and are making a significant fire assault on the mattress/mattress set. Each mattress set is subjected to a 19 kW flame on the top surface for 70 s and a 10 kW flame on the side for 50 s. The test proceeds for 30 min. In order to pass the test, the PHRR may not exceed 200 kW at any time. During the first 10 min of the test, the total heat release (THR) may not exceed 15 MJ. This value equates to an average flame size of 25 kW that is sustained for the full 10 min and does not take into account the 1.8 MJ of energy from the combustion of propane gas in the test burners.

The 16 CFR 1633 open flame test is much more severe than the 16 CFR 1632 smoldering test, in which 9 smoldering cigarettes are placed on the bare mattress and 9 between two cotton sheets on top of the mattress. In order to pass the smolder test, the char length at any cigarette location cannot exceed more than 5.1 cm (2 in) in any direction. The difference in flammability response to an open flame and a smoldering ignition source can be very dramatic. Significantly different mattress construction and materials may be required to pass the open flame ignition test than to pass the smoldering ignition test. For example, manufacturers were able to comply with 16 CFR 1632 using FR PUF and thermoplastic tickings, but more effective fire blocking technology (e.g., BF) is required in order to comply with the 16 CFR 1633.

For high risk and institutional occupancies, the widely used full-scale fire tests are California Technical Bulletin 121 [28] and 129 [5] (TB 121 and TB 129). These standards are the foundation of the NFPA 101® Life Safety Code (as designed under ASTM E 1590) and are recommended for healthcare, dormitory and other high risk installations due to their cost effectiveness, the thorough research leading to their use, and the match of test criteria to institutional use. In TB 129, a mattress is subjected to a 17 kW T-shaped gas burner on the side for 180 sec. The PHRR cannot exceed 100 kW over the 60 min test, and during the first 10 min, the THR and mass loss cannot exceed 26 MJ and 3 lbs (1360g), respectively. For institutional mattresses, fire performance is more critical than comfort and aesthetics.

Contributions to flammability

The flammability of a mattress depends on each of the components described above, along with the possible synergism or antagonism that may exist among component materials [29]. This section briefly describes some of the factors that have impact on mattress flammability and the severity of bedroom fires in general. A more detailed review of mattress construction and materials as they relate to flammability regulations and testing is under preparation [30].

Contributions to flammability: Construction

Mattress flammability is significantly impacted by its construction. The fuel load of a solid PUF core mattress is significantly greater than that of an innerspring mattress with similar filling

material. Intuitively, the fuel load would be expected to be an important factor in determining the fire performance of the mattress set. However, this assumption may only be partially accurate, since an innerspring mattress filled with melamine type foam has been shown to result in higher heat release rates than a solid core mattress of the same size filled with similar melamine type foam [31]. This may be attributed to the reduced airflow within the more closed structure of the solid core mattress, which limits heat release and fire growth, whereas the open structure of the innerspring allows air to flow freely. In the latter case only the types of materials used in mattress construction limit pyrolysis.

Contributions to flammability: Ticking

The flammability of ticking was briefly discussed in the section above. The most common ticking used in current mattresses are pile fabrics, knits, and jacquard woven fabrics. With an increased focus on allergies, physiological comfort, and fire safety, a variety of functional coatings (e.g., water-proof, anti-bacterial, anti-fungal, and/or FR finishes) are now applied to mattress ticking. The majority of modern ticking materials have a high polypropylene and/or polyester fiber count, with the fiber content varying significantly with the fabric structure and design pattern. These tickings are highly flammable, but are not necessarily a greater fire threat, as these synthetic fabrics tend to melt away from the ignition source and self-extinguish. Cotton tickings are often considered “sacrificial”, as they pyrolyze quickly and generate low heat, thereby resulting in little heat transfer to the inner layers of the mattress. While cotton, polyester and polypropylene fibers dominate the ticking industry, blends of luxury fibers (e.g., wool and silk) are becoming more prevalent. Wool and silk are inherently low flammability fibers. Fibers made from renewable resources (e.g., corn, soybean and bamboo) are also gaining popularity as more environmentally friendly alternatives. Viscose rayon derived from bamboo is of particularly high interest because of its inherent anti-bacterial and anti-fungal properties and its good breathability and moisture absorption [32]. However, very little is known about the flammability of these ‘green’ alternatives.

Quilting patterns are very common in mattresses. While quilting imparts more cushioning and insulation by creating large air pockets within the quilted structure, the quilting pattern itself also impacts the burning behavior. When tested under the cone calorimeter, composite specimens with quilted tickings exhibit slightly higher total heat release rates (THR) values as compared to non-quilted ticking specimens [33]. One of the probable reasons for this kind of fire performance is that flame spread in quilted specimens is slower. The quilted material therefore burns slowly but completely to give higher THR values.

Contributions to flammability: Interaction with nearby items

The mattress is only one of many contributing products dictating the magnitude of a bedroom fire. A bedroom frequently contains a bed covered with bedclothes (e.g., blankets, sheets, dust covers, and pillows), carpet, draperies, other furniture, and items that may be found both on and adjacent to the bed (e.g., toys, stuffed animals, and clothes). The purpose of requiring a conservative heat release metric for mattresses is to reduce the probability of a mattress-initiated fire spreading to other components in the room or a fire on one of the other items in the room igniting the mattress. Ultimately, the degree with which a mattress becomes involved and the severity of the fire will depend not only on the flammability of the mattress, but also on the flammability of other items on and near the bed, which may or may not have to meet

flammability requirements. For example, a recent study showed that the bedclothes, including sheets, comforter and blanket, on a queen size or larger mattress set are sufficient to take a standard room to flashover (>1000 kW HRR) [27]. To date, there are no federal flammability regulations for bedclothes.

2.2. Upholstered furniture

RUF is available in various styles, sizes, geometries, constructions, and materials intended to provide the consumer with the appropriate balance of function, aesthetics, comfort, durability, and cost. Examples of different RUF styles are provided in Figure 2. Predicting flammability of RUF is extremely difficult because of insufficient knowledge on how these variations in materials and design interact synergistically or antagonistically to influence flammability. Our current understanding of the relationship of RUF design parameters to flammability is primarily based on an extensive research project completed two decades ago [34].

Test Standards

In the U.S. and Europe, upholstered furniture (UF) used in public buildings and transportation are required to pass stringent open flame ignition tests (e.g., Cal TB 133 [7], ASTM E 1537 [35], BS 5852 [36], and/or FAA kerosene oil burner test for aircraft seating [37]). The most commonly referred to standard is Cal TB 133, which is a flammability test of the actual product (not a bench scale mockup). In this test, an upholstered chair is exposed to 18 kW flame from a square propane gas burner (with a gas rate of 13 L/min) for 80 s. In order to comply, the PHRR cannot exceed 80 kW at any time during the test, and the THR during the first 10 min cannot exceed 25 MJ. In addition, a toxicity metric requires smoke opacity to be less than 75 % and CO concentration in the effluent gases in the test room to be less than mass fraction of 0.10. Compliance may be achieved through some combination of BF, FR-PUF, and FR (back-coated) covering fabrics.

Currently, there is no federal flammability regulation for RUF. CPSC 16 CFR 1634 is a proposed regulation [9] that would require a composite assembly of PUF/cover fabric to be tested for smoldering ignition resistance in a mockup arrangement. For the cover fabric to pass the test, the mockup would not be allowed to smolder or transition into open flames during a 45 min test, and the mass loss of the PUF would be limited to 10 %. Failure would require a fire blocking material (e.g., BF) to be included in the mockup construction. The revised mockup must then comply with the same smoldering ignition requirements and an additional open flame ignition requirement. The smolder resistance criterion for a BF is more stringent than for the cover fabric. The mass loss of PUF is limited to 1 % when tested with a BF. The mockup with a PUF/BF/cover fabric must also pass an open flame ignition test. The open flame test is an exposure to a 240 mm butane flame for 70 s at the intersection of the seat and seat back in a mockup arrangement. Failure would result from a mass loss greater than 20 % from the initial mockup mass.

Contributions to flammability: Design (or Construction)

Depending on the design, and regardless of the amount of combustible material used, fire growth may be affected by the presence or absence of features such as gaps between major upholstered areas, armrests, tufting, welt cords, and open loop arms. As measured using Cal TB133, a

separated seat and back generally results in a lower HRR, because the back may not become involved in the fire [34,38,39]. Also, chairs with large gaps between the seat and the back are generally of a more functional design and contain less fuel. On the other hand, chairs with a separated seat and back provide a gap through which the flames from an intensely burning seat can readily reach the back support and accelerate flame spread. Upholstered chairs with no gap between the seat and the back generally contain more fuel and flames remain confined within the structure, thereby assisting fire growth. More luxurious upholstered chairs with armrests present a greater fire hazard, primarily due to the greater amount of flammable material and secondarily because the armrests can facilitate more radiative feedback to the seat, which can result in intense burning. The effect of tufting and welt cords depends on the type of combustion. In the case of smoldering fires, tufting and welt cords act as significant heat sinks, whereas for flaming combustion they act as flame arrestors.

RUF in which the upholstery is close to the ground (e.g., furniture with dust covers or short legs), result in rapid fire development and high HR values [38]. This is especially true if the furniture materials generate molten polymer drips (e.g., PUF and some thermoplastic fabrics), as this may result in pools of molten/degraded polymer that can easily ignite to form a pool fire, which can accelerate burning.

Contributions to flammability: Cover fabrics

Unlike mattresses, where the ticking fabric is more of an afterthought, for RUF the cover fabric is critical to the consumer since it is one of the RUF's primary aesthetic factors. To satisfy the large breadth of consumers' preferences, the cover fabric for a given design may be available in a large variety of materials, patterns, and colors, each of which impacts RUF flammability [13, 34,40,41,42,43,44]. For example, the European study, the Combustion Behavior of Upholstered Furniture (CBUF), showed that the cover fabric is the controlling element in small open flame ignition (e.g., from a candle) of RUF [34]. Since the completion of the CBUF study, covering fabrics have changed significantly. This is expected to impact RUF flammability [44]. Modern fabrics are generally constructed of blends of thermoplastic and regenerated cellulosic fibers, which are known to provide better durability and aesthetics, but in some cases, at the expense of flammability. Ohlemiller [13,14] observed that some thermoplastic fabrics, depending on fabric structure, may split open, enabling the underlying components (e.g., PUF and polyester wrap) to participate in the fire [45]. This resulted in a rapid increase in HRR and fire growth. To mitigate the increased flammability caused by these covering fabrics, fire blocking technologies were used in this study to delay ignition of the underlying components, thus allowing thermoplastic fabrics to be used while still complying with flammability regulations [13].

3. Fire Blocking Technologies for Soft Furnishings

The purpose of fire blocking technologies is to reduce the flammability of soft furnishings by preventing or delaying direct flame impingement and heat transfer from the flames or molten polymer to the core components. In addition to fire/flame resistance, other desirable properties of fire blocking materials include good handle and drape properties (which impact comfort), durability to wear and tear, cleaning, etc. (which impact service life), and neutral color (which may impact covering fabric appearance, especially for materials under white mattress tickings). As indicated earlier, the flammability behavior of soft furnishings is exceptionally complex

because of the large number of variations in materials, construction, and geometries. As a component of a consumer product, fire blocking materials must be cost-effective and not negatively impact the aesthetics, comfort, and durability of the soft furnishings. The number of fire blocking technologies (woven and nonwoven fabrics, FR coatings, and FR PUF) available is quite large to accommodate the requirements of consumers, manufacturers, and regulatory agencies.

FR Mechanisms: Passive and active modes

Fire blocking technologies operate by two broad, not mutually exclusive modes: passive and active [29]. Passive technologies are usually made from inorganic or inherently fire resistant organic fibers that are predominantly non-reactive and do not become chemically involved in the flames. Inherently fire resistant fibers used in this technology have high heat capacity and undergo an endothermic phase change in the presence of heat. Their effectiveness derives from serving as a physical and/or thermal barrier between some or all of the fuel and the potential ignition source. These passive technologies prevent or delay the ignition of interior cushioning materials; however, they do not prevent burning of the outer cover fabric.

Active technologies have a chemical effect on the fire. They can suppress the flames from the ignition source, prevent the outer upholstery from burning, and prevent the ignition of interior cushioning material. This essentially lowers the temperatures in a fire and reduces the generation of harmful smoke and gases [46]. Active technologies are combinations of fibers and/or coatings of fabrics, or PUFs with gas-phase-active FR for flame suppression or quenching. In general, passive technologies are good inhibitors of smoldering combustion, whereas active technologies suppress flaming combustion by altering either decomposition or oxidation reactions [47].

Barrier Fabrics

BFs are usually textiles that take the form of either an individual component or a layer within a composite of laminated layers. Depending upon the type of BF selected, a double upholstery process may be required. However, the use of a BF may facilitate the exchangeability of outer cover fabrics. Where BFs are not used, fire performance may be drastically affected by generic changes, cover fabrics, and other furniture components. In addition, the use of BFs may result in other trade-offs. For example, highly FR—and more expensive—cushioning materials may not be required. Also, FR treatments of cover fabrics may be unnecessary where appropriate fire blockers are used.

Placed on the surface or between components, BFs limit the product involvement in a fire by preventing and/or significantly delaying the ignition of a cover fabric and core materials, lowering the heat release rate, reducing the rate of flame spread and/or extinguishing the flames [43,48 49]. Often these BFs are placed between the exterior cover fabric and the first layer of the cushioning material in the furnished article. In order to meet specific flammability standards, more than one fire blocking technology may be used [50].

In general, BFs must conform to three different performance criteria: stability, integrity and insulation [51]. Stability implies that the BF construction remains intact when exposed to a fire or heat source (minimal shrinkage and hole formation). Integrity implies that the BF prevents

the pass-through of flames, heat, and volatiles (either through the BF itself or its char). Insulation refers to a minimal change in temperature of the unexposed face due to heat transfer through the barrier material. Minimal char shrinkage and retention of non-zero char tensile strength are other key factors in good fire resistance.

The barrier properties of a textile mainly depend on the fabric structure, the yarn construction, and the physical and chemical structure of the char resulting from a fire. The chemical and physical structure of the char determines the resistance to char oxidation. The fabric structure also determines the degree of air entrapment in the char. It is the char that often serves as the actual barrier between flames and the vulnerable contents of a soft furnishing product. Such chars are prone to oxidation during flame exposure, which effectively erodes the barrier, giving it a finite period of protection. This protection period depends on the nature of the organic fiber, minor contaminants in the fiber, the char mass per unit area and the temperature at which the char is exposed [52].

3.1. Barrier fabric types

As mentioned earlier, BFs used in soft furnishing applications are found in various forms. Generally, highloft, nonwoven fiber battings are used in residential mattress applications, whereas coated or laminated textiles are more common in institutional and upholstered furnishing applications. Types of BFs used in soft furnishings are mainly influenced by end user applications and cost. Structure, thickness, area density, and fiber blends of commercially available BFs used in soft furnishings are provided in Table 1. In this section, various fire blocking technologies are discussed with respect to material type, fiber content, and fire blocking mechanisms.

3.1.1. Woven BFs

Woven fabrics are generally more robust compared to their non-woven and knitted forms. One of the most important requirements of the upholstery manufacturing process is the stitching or sealing of the edges. For the BFs to be more efficient, the seams and stitches should remain intact even when exposed to thermal and mechanical stresses. This aspect of BFs is discussed in greater detail in the following Sections.

Structure

Woven fabrics have good mechanical properties and retain dimensional integrity even when exposed to heat and/or flame. The interlacing structure of warp and weft holds the decomposition products in place and eliminates the physical shrinkage of char. However, for open-weave structures in BF applications, the volatile gases from the heated PUF can easily find their way towards the flame, resulting in sustained burning. The situation is worse when the cover fabrics are thermoplastic, as the molten thermoplastic penetrates through the open weave structure and ignites the PUF core. For woven BFs to be effective, they must have a heavyweight construction (e.g., 300 g/m²), as the higher density fabric can prevent escape of pyrolysis gases and/or penetration of molten polymer [13]. The trade off is that higher area density and heavier weight can negatively impact the handle and drape properties, thereby affecting the formability, aesthetic, and comfort properties of the upholstered product.

High performance char forming fibers

In addition to fabric construction, fiber type is also critical to the attributes of BFs. Inherently fire resistant fibers (e.g., fiberglass, aramids, melamines, PBI, oxidized PAN, novoloids, pre-oxidized polyacrylonitriles and carbon fibers) are char forming fibers with high mechanical strength [53] that can be used for manufacturing BFs. Fabrics constructed from these inherently flame retardant fibers are expensive, and they are frequently used in high-performance applications (e.g., aircraft seating, seating in other mass transport vehicles and public buildings). BFs constructed of fiberglass are very effective at preventing an ignition source from reaching the PUF core, as the fiberglass is a high char-forming fabric with strong structural integrity [54]. Fiberglass fabrics (woven, knitted or non-woven) are often used as substrates for FR coating or laminating FR layers. The disadvantage associated with fiberglass flame barriers is poor durability (due to glass-to-glass abrasion) and lack of resiliency [55].

Fiber blends

The main disadvantage of inherently FR fibers is their cost. To reduce fabric cost and still maintain performance, manufacturers construct BFs as blends with other lower cost fibers. Fiber blending may occur before or during yarn formation stage. The less expensive thermoplastic polymers are not ideal candidates for BFs. BFs made solely from thermoplastic fibers often melt, shrink, and crack open [13]. Once there are openings in the BF the flames propagate to the PUF core, and the soft furnishing will burn as if there was no BF. However, this melting can provide an advantage if the thermoplastic is combined with a network support fabric (e.g., fiberglass matting or any char forming fiber fabric), as the thermoplastic can fill the voids of the network and thereby form a strong and durable fire blocking system [13]. Another alternative is to use FR thermoplastic fibers in conjunction with non-thermoplastic char forming fibers or thermoplastic fiber fabric backcoated with a char forming FR coating.

Natural fibers

BFs constructed of natural fibers (e.g., cotton) often produce a fire blocking char upon exposure to heat and/or flames. Cellulosic fabrics require chemical treatment (e.g., boric acid) in order to yield excellent fire resistance. FR treatment can be applied to the final fabric as a coating, or FR chemicals can be introduced during fiber formation to alter the polymer structure (e.g., FR rayon fiber). The FR rayon is generally used in RUF applications when combined with modacrylics, aramids, and wool fibers. For mattress applications, FR rayon fibers are usually blended with polyester fibers to form highloft battings. When exposed to heat, the FR viscose rayon decomposes endothermically and forms a silicate-containing protective char [52]. The low melt polyester fiber melts holds the protective char in place [56].

Core spun yarn

Another fire blocking technology uses core spun yarn to produce BFs. Core spun yarn (also known as core-sheath yarn) begins with an inherently fire resistant fiber core (e.g., glass). This core is then coated with a less expensive material (e.g., polyester) that is primarily responsible for the aesthetic and comfort properties. The thermally stable core maintains the structural integrity and provides a woven framework (grid) for the char layer (lattice) formed by the thermal decomposition of the sheath fiber. This type of “grid/lattice” structure [57] provides the physical barrier that prevents flame penetration into the more flammable cushioning layer as discussed earlier. The composition of the core and sheath can be tailored to satisfy fabric

performance requirements. For example, to further improve fire resistance the sheath layer may contain FR, and to improve strength and durability a polyester or polyamide sheath may be used instead of a cotton or polypropylene. Beside BF, the core spun yarn may also be used as sewing thread in upholstery.

3.1.2. FR coatings on woven BF or cover fabric

Another approach to improve the fire resistance of a woven fabric is to apply an FR coating to the outer cover fabric or BF. These coatings are attractive to the manufacturer as they can be applied to almost any fiber/fabric type. FR-treated fabrics only retard or delay the spread of flames as long as treatment chemicals are retained in the fabric. FR protection may be lost due to wear and tear. Some FR-coated BFs are functional for a short time but have serious drawbacks, including separation of the coating from the knitted substrate followed by balling up under the upholstery fabric and complete disintegration over a short period of time [58].

Coating placement

If the FR coating is applied to the inside face of the cover fabric as a backcoating, there may be little impact to the fabric aesthetics. However, when applied to the outside face or to both sides of the cover fabric, the fabric color, feel, and stiffness may be significantly altered. Although the aesthetics of laminated/coated fabrics may not be as desirable, these fabrics are often used to comply with the more stringent high occupant dwelling flammability regulations (e.g., Cal TB 133, Cal TB 129). While FR coated cover fabrics self-extinguish and exhibit limited flame spread, they do not perform well when exposed to large ignition sources even for a short duration as they have a tendency to form brittle chars that crack open and expose the more flammable core materials. Research has shown that FR backcoating improves resistance to small flames, but when tested with large ignition sources as in Cal TB 133 or CFR 1633, the increased heat release of the backcoating results in accelerated thermal decomposition of the underlying PUF [59]. As discussed previously, it is these types of unexpected interactions between the components resulting in a synergistic or antagonistic impact on pyrolysis that makes it difficult to predict soft furnishing flammability based on the flammability characteristics of the individual components.

Composition

A typical FR backcoating formulation used for upholstered cover fabrics consists of FRs (typically gas phase FRs), fillers, synergists and application ancillaries (e.g., polymeric resin binder, fabric softeners, and cross linking agents). Halogen-antimony FRs are frequently used and are very effective for both synthetic and natural fiber containing fabrics [60]. A halogen-containing polymer, combined with vinyl fluoride and finely dispersed antimony oxide, is commonly used for heavily used applications such as healthcare mattresses and mass transportation seating because it is significantly more difficult for the halogen to leach out when it is bound to a polymer rather than as a small molecule additive [61]. A drawback limiting this application is that halogenated polymers often require a plasticizer during processing, which can result in antagonistic reactions with other components of furniture [48] and itself may be a fuel for pyrolysis. Other common FRs are phosphorus derivatives, which improves smolder resistance, and aluminum trihydrate, which is endothermic and generates water upon heating.

3.1.3. Composite BFs

BFs created by bonding a highly fire resistant “layer” to one of the textile components are also commonly used in RUF. Bonding is generally accomplished by mechanical processes such as stitch bonding, needle punching, or thermal (heat bonding) processes. Adhesives can also be used for laminating various layers of BFs.

Composite or laminated fabrics offer two advantages. First, they eliminate the labor involved in sequential upholstering of fabric layers, and second, they prevent exposure of underlying cushioning materials by ‘crack-opening’. When the multi-layered BF is exposed to flames, the heat is taken away by the outer coating or layer of the composite fabric, leaving the underlying substrate to which the coating or outer layer is laminated intact and preventing the involvement of underlying cushioning materials in the fire. For example, when a glass fiber fabric coated with polyvinyl chloride is exposed to flames, the polymer does not shrink away from the underlying glass fiber fabric. Instead, it softens and flows into the interstices of the glass fiber fabric. Laminated/coated fabrics eliminate the air space between the layers of BF and maintain the aesthetics of the exterior fabric while still providing better fire performance [48,62].

Another example of a fire resistant laminated fabric is an aluminum foil liner constructed of a very thin layer of aluminum sandwiched between a woven fiberglass and spun fiberglass. Since these types of BFs are quite thin and flexible, they do not impart stiffness to the RUF when placed between the fabric and the filling. Thin layers of FR PUF laminated or backcoated onto various textile substrates are in use as BFs in mattresses and RUF. Their major drawback is cost, as they can be an order of magnitude more expensive than other fire blocking technologies.

Multi-layered BF structures comprised of fabrics made from layers of structural char-forming, heat-absorbing and inherently fire resistant fibers have also been suggested [63,64]. Such multi-layered structures have fewer open cracks and holes when exposed to open flames.

3.1.4. Nonwoven BFs

Nonwoven fabrics are low density fabrics characterized by a high ratio of thickness to weight per unit area [65]. Intermingled fibers are compressed or densified by the process of either needle-punching, stitch-bonding or thermal-bonding. The term nonwoven is used in the textile manufacturing industry to denote fabrics that are neither woven nor knitted. Nonwoven BFs are generally less expensive than woven and knitted BFs. However, disadvantages associated with their manufacturing techniques, such as uneven blending, regions with uneven area density etc., affect their performance as BFs. Nonwoven materials typically lack strength (tensile and bursting) unless densified or reinforced by a backing. Due to their structural characteristics, nonwovens also have challenges associated with their mechanical performance and thermal shrinkage when exposed to heat. Thus, good quality control measures are critical during manufacturing.

Loft

The weight or thickness of a nonwoven fabric is reported by a term called loft. Highlofts have low density with a greater volume of air than fiber. Generally, highlofts with a thickness ranging

from 7 mm to 51 mm and a basis weight of 75 g/m² to 375 g/m² are preferred for soft furnishing applications. When exposed to an open flame ignition source, highloft BFs containing char-forming fibers form a thick char that blocks the flow of oxygen and volatile decomposition gases and also slows heat transfer by creating an effective thermal insulation barrier [66]. Highloft high porosity structures also inhibit flame spread. An alternative to a highloft material is compressed layers of a flame retardant nonwoven material that expand when exposed to heat and provide a thermally thick barrier [67].

Fiber type

Nonwoven battings/BFs of inherently fire resistant fibers and natural and/or synthetic fibers have been reported [52,66, 68, 69 ,70,71]. These blends are designed to withstand extended periods of exposure to open flame and to prevent the underlying materials from igniting. The proportion and the type of fire resistant fibers used depend on balancing cost and flammability performance of the soft furnishing. In addition to the cotton and typical synthetic polymers already discussed (e.g., polyester), battings have also been constructed using other natural fibers such as flax, jute, hemp and wool, but their use has been limited by difficulties in processing [72,73,74,75,76].

Cotton treated with boric acid

Nonwoven cotton battings treated with boric acid have been used for many years as BFs in soft furnishings products, especially mattresses [47]. These materials are the least expensive FR barrier materials available on the market, since they usually contain cotton fibers that are procured from textile mills as by-products or waste products. Boric acid catalyzes dehydration reactions of the oxygen-containing fibers and facilitates char formation [77]. When exposed to an open flame, the boric acid decomposes endothermically to release water and cool the flame. The glassy coating formed by the decomposition of boric acid suppresses the release of volatile species from the underlying fuel and acts as an oxygen barrier, thereby preventing further oxidation of volatiles. Because of the low intrinsic toxicity, boric acid and borates can be safely used in consumer products [78]. However, boric acid treatments may have problems associated with chalking, color change and undesirable texture.

In soft furnishings products, nonwoven FR cotton batting is helpful in meeting various flammability requirements, including the cigarette ignition ASTM D5238-98 test (sandwich batt test), the open flame Cal TB 117 test (both vertical and horizontal burning) and the large-scale Cal TB 129 and 16 CFR 1633 tests [79]. Various methods to enhance both smoldering and flaming resistance of cotton battings have been explored. BFs constructed of cotton blends with inherently flame retardant fibers (e.g., FR-modacrylic, FR-polyester, and FR-viscose) enable soft furnishings to comply with various cigarette resistance and open flame resistance regulations. The slow combustion of cotton battings in soft furnishings, especially mattresses, is the critical element that allows sufficient egress time for humans to react to the fire. The disadvantage, however, is that these BFs are very bulky and hence rarely used in RUF.

Polyester fiber

Polyester fiber battings, commonly used in upholstered seats, provide a significant barrier effect when tested with smoldering cigarette ignition [80]. However, it fails to protect the underlying cushioning material when an open flaming ignition source is used [49]. The polyester fiber melts away from the smoldering cigarette and extinguishes, whereas the polymer melt burns in the

presence of flaming ignition. Once ignited, the molten polymer burns vigorously, resulting in substantial weight loss and increased temperature of the system. Thus, the polyester fiber batting acts as an additional fuel and the whole system fails. Recent studies on the flammability of cushions with polyester fiber wraps (low loft batting) in our laboratories have shown that the presence of polyester wrap increases the pHRR when compared to analog systems without polyester fiber wrap [81]. This study suggests that, regardless of the type of FR-PUF and/or cover fabric, polyester fiber promotes the composite system to burn vigorously.

Organic and inorganic fiber blends

Horrocks [82] developed a novel BF comprised of a flexible nonwoven core containing both organic and inorganic fibrous components. The core is constructed such that it permits flexibility at both low and high temperatures. When exposed to temperatures below 500 °C, the engineered fabric accommodates expansive forces generated by the developing intumescent char component by increasing in volume and thickness while still maintaining its structural integrity and flexibility. These composite structures have a unique flame and thermal protective behavior that enables the fabric to respond to an incident heat flux in a manner that initially enhances its protective property following intumescent char formation. At higher temperatures, this protective property is reduced but not destroyed, as it is in the case of high performance fabrics containing aromatic and carbonized fibers. These barrier materials, however, were not tested for open flame ignition performance.

The latest development in nonwoven BFs is the siliconized thermally bonded highloft BF. The siliconized highloft is a blend of three different types of siliconized fibers held together with a low-melt polyester [66]. Each component of the blend provides a specific and necessary functionality to the barrier material. The one form of siliconized fiber provides a non-shrinking form of carbon, whereas the other type of siliconized fiber improves the softness and water repellency of the blend. The regenerated cellulosic fiber is very cost effective and can be used to increase the bulk of the product. Siliconized modacrylic fiber, when used in an appropriate blend ratio, can reduce the local oxygen content within the barrier during a fire, thereby prolonging char oxidation. The low melt polyester provides resiliency to the barrier, and its strong thermoplastic character helps to maintain the structural integrity of the char formed.

3.2. Polymeric foams

Typically, soft furnishings contain standard PUF as the filling/cushioning component. The PUF is inherently flammable unless treated with an FR additive (e.g., halogen and halogen-phosphorous [83], which are traditionally gas-phase acting FRs). Over the past decade many FRs have been banned due to environmental, health, and safety (EHS) concerns, and many are under scrutiny [84, 85].

An innovative and potentially green FR approach with potentially strong commercial viability is to create a fire blocking armor on the PUF or fabrics using a thin polymeric coating containing fire retardants (to be discussed in the Future Trends on Fire Blocking Technologies section). Other halogen-free FRs now in the research stage are PUF containing a combination of ammonium polyphosphate, pentaerythritol and melamine (an intumescent coating) and PUF impregnated with graphite [86].

Lower flammability polymer

Another approach to reduce the flammability of foam is to use a foam based on a lower flammability polymer. Intrinsically FR foams (e.g., polyimide foam) are more commonly used in higher risk environments (e.g., aircraft and spacecraft seats) where their higher cost is justified by the additional fire safety necessary to comply with strict flammability regulations. These foams may be harder to ignite, have lower HRR, have higher thermal stability, etc. For example, a polyester foam was evaluated by CPSC in the early 1990s as resistant to cigarette ignition. This foam exhibited superior resistance to smoldering ignition sources, but was more easily ignited by open flames (as compared to PUF) [31]. Polyester foam is not commonly used in soft furnishings due to higher cost and durability issues (e.g., hydrolytic degradation).

Encapsulation

A cost-saving approach is to create a composite of a PUF core encapsulated by one of these intrinsically FR foams. For example, Hashish [87] evaluated a polyimide foam as a fire barrier for spacecraft cushion material. When tested by cone calorimetry, the application of polyimide foam layers over standard PUF increased the minimum heat flux for ignition of flammable PUF from 27 kW/m² to 48 kW/m². This ignition risk reduction was sufficient to enable the noncompliant PUF to pass the targeted regulations. Inclusion of polyimide foam layers also significantly reduced the PHRR, MLR, and the generation of smoke and carbon monoxide. Carboxylated chloroprene foams are also commonly used to encapsulate the PUF core or as a fabric backing. Chloroprene foams are high density foams which are generally specified for public transport applications. They generally act as active fire barrier materials.

4. Performance of Fire Barriers

Successfully achieving the desired level of fire protection requires appropriate matching of BF to the desired characteristics of the soft furnishing. This selection is generally a process of trial and error due to significant measurement science gaps (e.g., how does the construction of RUF impacts RUF flammability). Below are a few examples demonstrating the complexity that makes a priori selection of BFs difficult.

4.1. Impact of BF on flammability of mattresses

Innerspring mattresses

The impact of BFs on the flammability of innerspring mattresses with different filling materials is shown in Figure 3 [29]. Regardless of the filling type (e.g., standard PUF, polyester fiber batting/PUF, or a cotton batting/ felt), these innerspring mattresses were able to pass the open flame ignition test for mattresses (TB 129 [5]) designed for high occupancy dwellings, with a 100% success rate using a BF (e.g., fiberglass fabric). The test criteria for passing TB 129 limits maximum heat release rate to 100 kW, total heat release in the first 10 min of the test to 25 MJ and weight loss to 1.36 kg (3 pounds). This essentially requires complete protection of cushioning materials from heat and flame. Without the BF, the same mattress construction had inconsistent TB 129 performance with the degree of failure depending on the type of filling material. For example, PUF innerspring mattresses had a success rate of 44 %, signifying four passes out of 10 tests [29]. The cotton batting/ PUF innerspring mattress and polyester fiber

batting/cotton felt/PUF innerspring mattresses yielded a success rate two times greater at approximately 88 %. Innerspring mattresses with a polyester fiber batting combined with an insulator pad and PUF or cotton batting had a 100 % TB 129 success rate without using a BF.

Solid core mattresses

In this same study, the researchers determined that solid core mattresses passed TB 129 without using a BF [29]. This is presumably a result of restricted airflow in a solid core mattress, which restricts the entrainment of oxygen needed to sustain pyrolysis. This suggests that under the right constructions and with the right combination of materials it may be possible to pass TB 129 without using a BF. However, this does not necessarily provide a product that is desirable by the manufacturer or consumer (e.g., it may not be comfortable, attractive, or cost-effective).

Interaction with tickings

Tickings perform differently in the presence or absence of BF. A majority ($\approx 80\%$) of mattresses with a polyvinyl chloride (PVC) ticking pass the TB 129 without using a BF because PVC tickings are active fire barriers with self extinguishing behavior [29]. Approximately 20 % mattresses with PVC coated ticking fail due to antagonistic reactions of highly plasticized PVC coated fabrics with other components of upholstery. Mattresses with cotton/fiberglass ticking do not require an additional BF layer to protect the underlying cushioning layer either. In this case, the cotton/fiberglass ticking acts as a passive fire barrier and physically prevents flame and heat transfer to the underlying cushioning layer. On the other hand, mattresses with cotton ticking certainly require a fire barrier in order to pass the open flame test. This is partly because cotton is extremely flammable and cotton tickings burn with a higher rate of flame spread, thereby exposing underlying cushioning layers to the open flames.

Institutional vs. residential mattresses

The materials and constructions discussed above for passing TB 129 are generally used for institutional mattresses. For institutional mattresses, fire performance is more important than comfort and aesthetics. However, polyvinyl tickings, fire barriers with fiberglass substrates, and solid core mattresses with densified polyester batting are not preferred choices for residential mattresses due to cost, comfort and aesthetics. Unlike institutional mattresses, comfort and aesthetics are of primary importance in the case of residential mattresses; hence, fire performance must be achieved while still maintaining the comfort and aesthetics. For this reason, highloft BF are more commonly used as fire barriers in residential mattresses. Ticking with polyester or polyester blends that are generally used in residential mattresses behave very differently in presence of fire barriers. The effects of melting and dripping can have a varied impact on the flammability of a mattress. Data for compliance to 16 CFR 1633 for residential mattresses with highloft or other newly engineered BFs are currently not available. Several polyester blend tickings are being currently investigated and their fire performance with and without BFs being studied in our laboratories.

4.2. Impact of BF on flammability of upholstered furniture

Cover fabric

The impact of a BF on the flammability of upholstered seating has been extensively investigated by Damant et al. [39, 43], who used the Cal TB 133 test for comparison. The test criteria for

passing TB 133 limits maximum heat release rate to 80 kW, total heat release in the first 10 min of the test to 25 MJ and weight loss to 1.36 kg (3 pounds). The test also has smoke and carbon monoxide limitations [7]. With a BF, most cover fabrics will have a greater than 85% passing rate, which is 10 % to 50 % better than that achieved without using a BF. However, the level of confidence in passing the Cal TB 133 test depends on the type of cover fabric. In the case of poorly performing cover fabrics, the use of BF is essential to pass Cal TB 133 test (Figure 4). Using a nylon /polyester or polyolefin cover fabric with a BF provides a chance of passing of 70 % (3 out of 10 replicates failed); whereas chairs with polyester or wool/nylon cover fabrics had a higher chance of passing (90 %).

In a separate study [42], a range of BFs and cover fabrics used in upholstered furniture were tested in a mockup seating arrangement, and their individual as well as combined responses to cigarette ignition, small open flame, and wooden crib tests were reported. A description of the cover fabrics is provided in Table 2, with flammability results separated by ignition source and BF type summarized in Table 3. In the absence of a BF, all the cover fabrics passed the smoldering ignition test (cigarette ignition source) but failed the small open flame (butane gas flame ignition source) and crib ignition tests. The exceptions to these results were FR polyester and silk cover fabrics, which self extinguished once the butane flame and burning crib were removed. In the absence of a cover fabric, all the BFs passed the smoldering test, butane flame and crib ignition tests, except for the 100 % cotton, which only passed the cigarette and small open flame ignition tests. This data suggests that the type of BF appears to impact the ability of the cover fabric to pass both the smoldering and open flame ignition tests. For example, the 100 % cotton (cover fabric II) failed the butane flame ignition tests when combined with all BFs except the 100 % cotton. The same cover fabric (100 % cotton) failed the smoldering ignition tests for the 100 % cotton (220 g/m^2), the novoloid, and the melamine based BFs. Another example is the BFs that contain inherently flame retardant fibers (e.g., polyaramids, phenol-aldehyde, melamine and modacrylic), which were resistant to all three ignition sources, although their fire performance was altered by the type of cover fabric. Most BFs tested failed the cigarette ignition test in the presence of 100 % cotton cover fabrics (the cotton twill and cotton corduroy). This study concluded that some cover fabric/BF combinations appear to be effective in protecting the PUF from a flaming ignition source but do not always provide the same protection from a smoldering ignition source. This is derived from the fact that none of the cover fabrics ignited from a smoldering cigarette when tested by themselves, yet ignition occurred when the barriers were combined with certain cover fabrics.

Barrier effect mechanisms

In a separate study, Ohlemiller [13] concluded that the barrier effect is more physical than chemical. In this study, the researchers measured the impact of HRR by changing the BF and covering fabrics over a Cal TB 117 complaint PUF [88]. The PUF/BF/cover fabric specimens were tested in the cone calorimeter at 35 kW/m^2 heat flux. The cone data indicates that woven glass fabric yields a lower averaged HRR regardless of the cover fabric type than do aramid fiber fabric or knitted fabric with a glass and charring fiber blend (Figure 5). Similar results were obtained when composites were tested without a cover fabric. A knitted fabric with a glass fiber blend used as a BF fails to protect the underlying PUF from heat. In this case, the flames from the burning cover fabric propagate through a relatively open knitted structure and ignite pyrolysis gases from the heated PUF, whereas the tightly woven glass fiber fabric significantly

prevents the escape of pyrolysis gases from the underling PUF. For all the fabrics tested in this study, the HRR (not shown here) for nonwoven aramid fabric and knitted glass fabric showed two distinct peaks: the first peak was dominated by the cover fabric and the second peak by the PUF. The testing of woven glass fabric invariably showed a single peak, from the burning of the cover fabric alone. Thus, not all fire barriers succeed in protecting the PUF from the heat. The level of protection depends on the fiber type, the construction of the BF and the type of cover fabric.

4.3. Performance assessment of BFs

Failure Mechanisms: Shrinking and char strength

One of the failure mechanisms for BFs is the stress-induced separation/splitting of BF that results in exposing the cushioning materials of the soft furnishing to high temperatures and flames. When exposed to heat and/or flames, the BF undergoes chemical and/or physical changes (e.g., dissipation of heat, release of FR, and formation of a protective char), and that may cause the BF to shrink, become stiff and/or brittle, and/or become thinner. The unexposed/unshrunk BF exerts a force on the shrinking char, causing the BF to split open. The extent of the physical deformation is affected by the type of BF used. For example, a knitted BF will split open to a greater extent than a woven or nonwoven BF [13]. The force that the unexposed BF exerts on thermally degraded BF is dependent on the length and pre-tensioning of the barrier, as well as the “anchoring” forces on the barrier in the specific application. For example, the force seen by an area of BF on the top of the mattress may be lower than on the side as a result of the absolute amount of shrinkage caused by the greater length of the spring (unexposed fabric) on the top versus the side. The mattress application of BF is complicated by the fact that the BF may be sewn tightly to other layers (ticking and back scrim) whose mechanical properties also affect, and potentially dominate, the amount of pulling stress on the BF. In addition, the edge conditions, and in particular the extent to which they inhibit shrinkage-induced movement, vary considerably with mattress design. The situation for upholstered furniture is more complicated, as the BF is stretched over a three-dimensional geometry. Thus, the performance of a barrier material in a given type of application may depend appreciably on the specific details of that application as well as on the properties of the BF itself. Nonetheless, an important measure of BF effectiveness is the extent to which it shrinks under heat exposure given the tensile properties of the resulting degraded material. Currently, there are no well defined test methods to determine char strength and shrinkage potential of BF. Some industries determine char shrinkage or hole formation in the BF by exposing the specimen to a Meeker burner (Figure 6) for a specified duration. The test is purely qualitative. The chars for some BF tested using this method are shown in Figure 7. Nonwoven felts of inherently fire resistant fibers such as para-aramid, melamine and meta-aramid form a protective char when exposed to an open flame. Meta-aramid char is more brittle as compared to para-aramid char. The synthetic fiber felts (modacrylic, rayon, and polyester) melt and shrink away from the flame.

Failure mechanisms: Thermal degradation

Another common failure mechanism for BFs is heat penetration at sufficient levels to cause thermal degradation of PUF and generate highly combustible gases. The BF can still be structurally intact (no splitting) while the heat is transferred to PUF. When heated, PUF can collapse to form a pool of molten polymer. ASTM D7140 is a standard test for measuring the

thermal penetration performance of BF that is intended to be used in soft furnishings [89]. The BF is exposed to a well-defined and controlled convective (open-flame) heat source for 60 seconds (Figure 8). This test method essentially measures the heat transfer of textile materials and determines whether the heat transferred through the BF is sufficient to ignite underlying materials.

Test standards: UFAC smoldering ignition test for BF

The Upholstered Furniture Action Council (UFAC) has defined a BF test method to measure the performance of a BF exposed to a smoldering ignition source. The UFAC test method is voluntarily used by many upholstered furniture manufacturers [90]. The smoldering ignition assessment is conducted on a mock up composite (Figure 9) and is intended to define the minimum BF performance level (cigarette ignition resistance) necessary to prevent ignition of a standard PUF covered with a smolder prone/ignitable fabric (Class II cover fabric). This test is based on the BS 5852 Part I test method [36] to test the ignitability of an upholstered composite to a smoldering type of ignition source. For the BF to pass this pass/fail test, the composite cannot ignite and the vertical char length cannot exceed 38 mm upward from the crevice [90]. Generally, BF with high area densities and highloft constructions pass this test. ASTM had a BF component test (now obsolete) to assess the smoldering ignition resistance of cotton battings. The ASTM D 5238 [91] test method is more severe than the UFAC smolder ignition test. In this test a lighted cigarette is placed between precut and preconditioned pieces of cotton battings (Figure 10), and the length of char is measured as soon as smoke is observed. Failure is defined as char lengths of 25.4 mm (1in) or greater.

Test standards: BHFTI smoldering ignition and open flame tests for BF

BHFTI has no specific test for the BF component. The smoldering ignition test for upholstered furniture described in Cal TB 116 [92] does not mention the use of BF, but it does require the finished product or the prototype mockup to be tested with the actual components of the product sold. The Cal TB 117 [93] requires the cover fabric and the loose fill materials with BF to be tested for open flame ignition resistance. TB 117 does not have a specific open flame ignitability test just for BF; however, the proposed draft describes open flame ignition tests for cotton battings in both vertical and horizontal orientations. For the vertical open flame test, the flame application time is 10 min with a flame length of 102 mm (≈ 4 in), and for horizontal testing a gas flame with energy output of 0.016 kW/h is used. To pass the test, the cotton batting must self-extinguish by the end of the 10 min test time and the mass loss must be limited to 4 % of the initial mass [79]. The test is further modified for the mattress application with a larger sample size (30.48 cm x 30.48 cm (12 in x 12 in) test specimen) and a flaming ignition source simulating the 16 CFR 1633 flame. The specimen is tested in the vertical as well as horizontal orientation (Figure 11). The temperature on the opposite side of the specimen is recorded using an infrared (IR) instrument. One of the most important observations during and after the test is a visual grading of the char formation. This test is material specific (exclusively for battings with at least 70 % cotton) and hence has a limited application. BFs with constructions other than nonwoven battings (thermally thin BF) may not withstand this severe test.

Test standards: BF development and quality control

The ASTM and UFAC tests are commonly used in the development and quality control assessment of BFs. For non-woven, highloft battings, quality control measures generally include

the measurement of weight, thickness, uniformity, and a burn test (draft proposed TB 117(10)). These tests are qualitative, with specific guidelines for assessing fire performance of the BF. Since BFs are generally expected to be self-extinguishing, other test methods for such fabrics include measurements of the time of afterflame and afterglow and the extent of fire damage in terms of char length, hole size or weakened sample length.

Bench scale test methods

In an attempt to develop a clearer picture of burning behavior and to quantify a number of aspects of the BF performance, it is necessary to define simple bench scale test methods based on fundamental and scientifically sound principles. Due to the economic burden of full-scale tests, these bench scale tests should empirically correlate with the full-scale performance of the product and must have predictive power. The largest hurdles in developing predictive tools have been discussed throughout this review. The flammability can drastically be impacted by the construction of fabrics and of the finished product, the type of materials, and other factors, which may mean that it is not possible to predict the full-scale behavior of the BF without testing the BF in the context that defines the final product (e.g., RUF with the specific covering fabric/PUF and /filling). However, the existing test methods described below could be helpful in screening barrier materials, thereby avoiding expensive and time-consuming full-scale furniture/mattress tests.

Limiting Oxygen Index (LOI) method

According to the ASTM D2863 test [94], the limiting oxygen index (LOI) is defined as the minimum concentration of oxygen, expressed as a volume percent, in a mixture of oxygen and nitrogen that will support the flaming combustion of a material. This technique provides a numerical measure of sample flammability, although it does not explain the burning behavior of the material. Generally, textiles having LOI values of 21 or less burn rapidly in air, which has an oxygen concentration of 21.6 %. Textiles with values in the range 21 to 25 burn slowly, and those with $LOI \geq 26$ exhibit some level of flame retardancy. LOI tests are primarily used to determine the relative effects of different flame retardant treatments and finishes, varying add-on finishes, or varying synergistic combinations of flame retardant compounds. However, because LOI values may be influenced by many fabric variables for a textile comprising a single fiber type, this test method is rarely used to define fabric performance by regulatory and commercial bodies [95]. LOI methods, however, do find applications as research and development tools [96].

Thermal stability

The thermal stability of BF can be studied by thermal analysis using thermo gravimetric analyzer (TGA), thermo mechanical analyzer (TMA) or dynamic thermal analyzer (DMTA) techniques. Mass loss measurements at appropriate incident heat fluxes relate to volatilization and initial char formation, full char development, and subsequent char oxidation [97]. Resistance to char oxidation is a particularly desirable characteristic, since deterioration would eventually result in a failure of the BF to protect the PUF core.

Thermal conductivity

BFs must limit thermal transfer into the product via conduction, convection, and radiation. As discussed above in reference to ASTM D 7140, high thermal penetration through the BF can

cause the PUF core to ignite and accelerate the flame spread even when the BF is physically intact. Thermal conductivity measures the rate of conductive heat transfer through a material. This property will vary with the amount of heat energy that a material is exposed to, and is therefore moderately temperature dependent [98]. Thermal conductivity measurement of materials can be useful in assessing their effectivity as BF and, to some extent predicting their performance in ASTM D 7140).

Thermal Protective Performance (TPP)

One method for screening materials for their suitability as BF is to measure the thermal protective performance (TPP) upon exposure to an incident heat flux (Figure 12). The ASTM Test Method D4108 [99] can be used for this measurement. Developed by DuPont, this test method was originally designed to evaluate the thermal insulation properties of fabrics and thereby predict the incident heat energy on the outer surface of fabric systems that could cause 2nd degree burns on human skin. For this application, the test specimen is exposed to a standard flame, and a calorimeter measures the heat flux through the specimen. A thermocouple in direct contact with the back surface of the specimen measures the thermal protective temperature (TPT). To characterize barrier materials, the specimen would be exposed to an incident heat flux for a specific time period. Low TPT values imply good insulation properties, which will help prevent the underlying cushioning from the heat and flames. The test method is applicable to woven materials, knit materials, battings and nonwoven materials.

Unexposed face temperature

The temperature of the unexposed face could also be one of the criteria for assessing barrier performance [51]. The rationale for this idea is that a rise in temperature on the unexposed side of barrier materials could ignite volatiles from underlying filling materials, thereby leading to fire propagation.

Air permeability

BFs used in soft furnishings are porous materials. The size of pores defines the rate of air permeability, which in turn impacts the burning rate of materials within the barrier. The permeability should be kept low enough to prevent flaming combustion inside the BF, especially when pyrolysis gases accumulate underneath the barrier. Air permeability of a BF before and after heat exposures could give insight into changes in porosity and whether or not the material will act as a barrier to oxygen entering the combustion zone. The ASTM D 737 [100] standard describes the method for conducting an air permeability test for various textile materials including woven, nonwoven, and knitted fabrics.

Tensile strength

Measurement of the breaking strength of samples exposed to various heat fluxes can give insight into the loss of tensile strength due to heat exposures. Determination of the breaking strength of a pre-tensioned sample exposed to a specific heating condition could be too complex, poorly defined and less reproducible. To address this issue, a simple test apparatus has been developed at the Engineering Laboratory at NIST that enables pre-tensioning of the BF and exposure to heating conditions seen in real fires. The strength of the charred BF sample is measured, post exposure, by adding additional weights until the char fails in tension. Test results for existing BF that are now being used successfully in real applications can be used to judge new BF

approaches. This NIST developed tool is still in the prototype stage, and require more testing before it is validated, but the initial results seem promising. A test protocol is expected to be released in the fall of 2012.

5. Future Trends in Fire Blocking Technologies

Soft furnishings manufacturers are complying with current flammability regulations, and will likely continue to comply in the future with proposed flammability regulations, by using BFs. However, engineering and technical options to reach compliance are quickly diminishing because of mandated sustainability regulations for consumer products, such as REACH [101], EcoLabel [102], and Environmental Product Declaration (EPD) requirements [103]. Almost all halogenated flame retardants may be withdrawn due to the associated potential health and safety and environmental hazards during manufacturing, end-use, and disposal. Information on halogen replacement technologies is available in the literature [104,105,106,107] and is beyond the scope of this review. The increased focus on sustainability of the final product suggests that future FR technologies not only need to satisfy these sustainability regulations, but also need to improve the fire safety of new more sustainable products, which may have different flammability issues (e.g., carbohydrate-based FR for a soy-based foam).

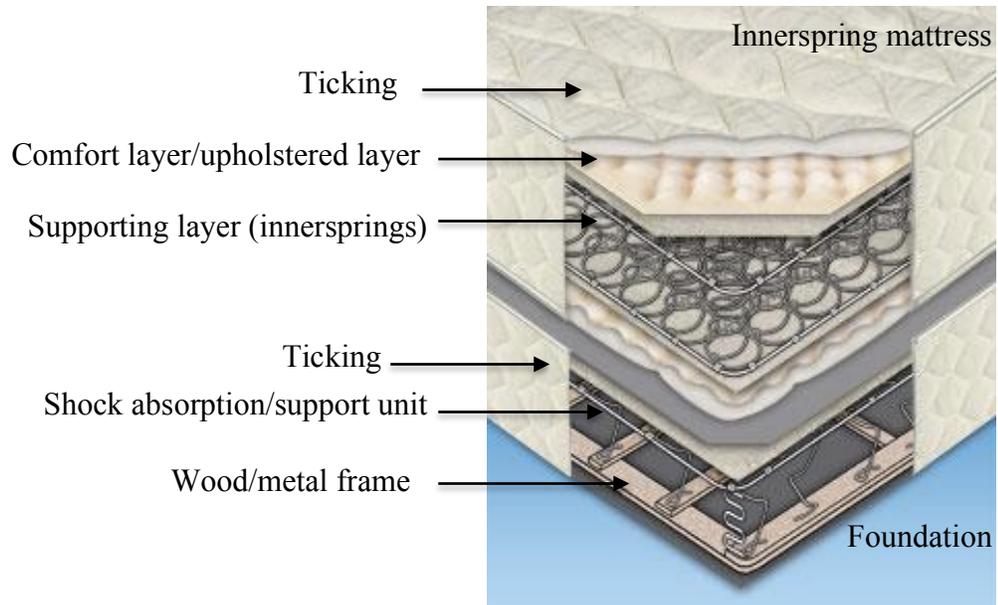
The nanoclays currently used to reduce flammability do not have any EHS restrictions. These nano-FRs are known to significantly improve the mechanical, thermal, barrier, and flame retardant properties of the base polymer. Polymer/clay nanocomposite fibers and nanocomposite coatings for textile applications have demonstrated significant reduction in flammability, increased tensile strength, and reduced thermal shrinkage of the fabrics [108,109]. However, the processing of polymer/clay nanocomposites is challenging in terms of maintaining nano-dispersion, and the influence of nanoparticles on rheological properties can be significant, particularly during fiber extrusion.

An innovative approach to address these challenges using the same nano-FRs is to apply a coating to the fabric or PUF after manufacturing. A novel coating method using a layer-by-layer (LbL) deposition technique is a water-based approach to fabricate nanometer- to micrometer-thick coatings on the substrate. Thin film coatings (≈ 350 nm) have 50 % mass fraction of nano particles, but the actual loading of nano-FR is less than 1.6 mass fraction % of the coated substrate. This is significantly less than most commercial FR levels (≈ 10 % to 30 %) that are used in thermoplastic applications [83]. The process is highly tunable, which allows for coating polar substrates using any polymer and FR that can be dissolved/suspended in water. Another advantage of LbL coatings is that the thin film coating on the surface of the substrate is uniform and does not change the bulk properties of the substrate.

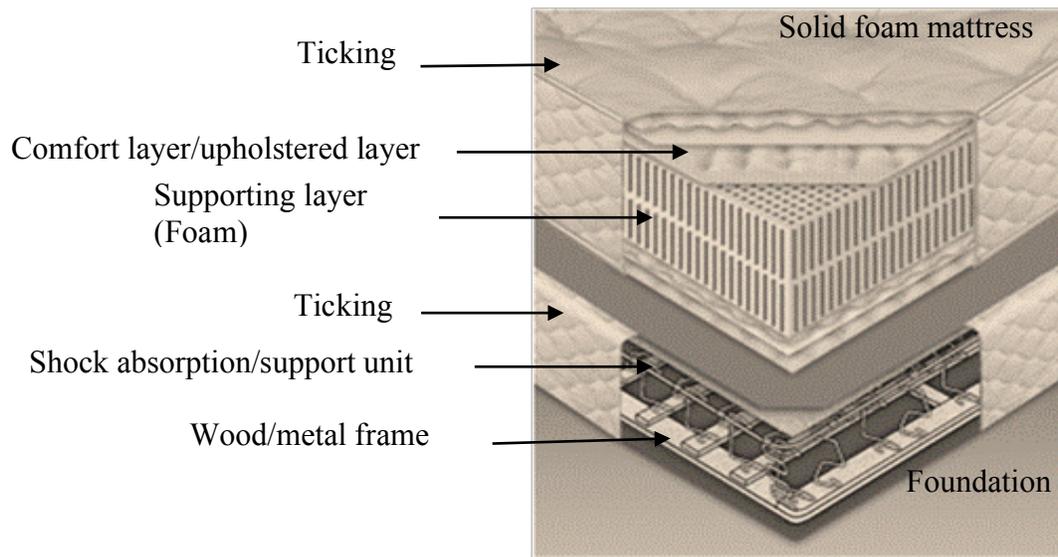
Preliminary efforts in reducing the flammability of PUF by incorporating carbon nanofibers (CNF) [110] and multi wall carbon nanotubes (MWCNT) [111] into LbL-fabricated thin film coatings have shown promising results. These LbL coatings were found to significantly reduce the flammability of PUF, with 55 ± 6 % reduction in pHRR and 21 ± 3 % reduction in total burn time. This reduction in flammability of the LbL-coated PUF is significantly better (≈ 50 % greater reduction in PHRR) than that reported for CNFs embedded directly into the PUF and other flame retarding technologies commercially used in PUF [83]. This research has laid the

foundation for using LbL to fabricate coatings on PUF and BFs using a range of nanoparticles and other performance enhancing additives. Davis and Grunlan continue to work on fabrication and analysis of clay coatings, cellulosic fiber coatings, and mixed additive coatings on both PUF and BFs. In addition, assessing the release of nanoparticles during aging and measuring the change in fire performance due to aging is ongoing.

These newly engineered materials, which address environmental as well as toxicological concerns, may lower heat release in future soft furnishing fires, thereby saving lives and protecting property in case of accidental fires.



(a)



(b)

Figure 1. Schematic of a typical residential mattress and foundation set: (a) innerspring and (b) solid foam.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 2. Examples of upholstered furniture: (a) stacking chair, (b) stacking chair with no cushioning on the back, (c) office chair, (d) fully upholstered chair, (e) lounge chair and (f) two-seat sofa or love seat.

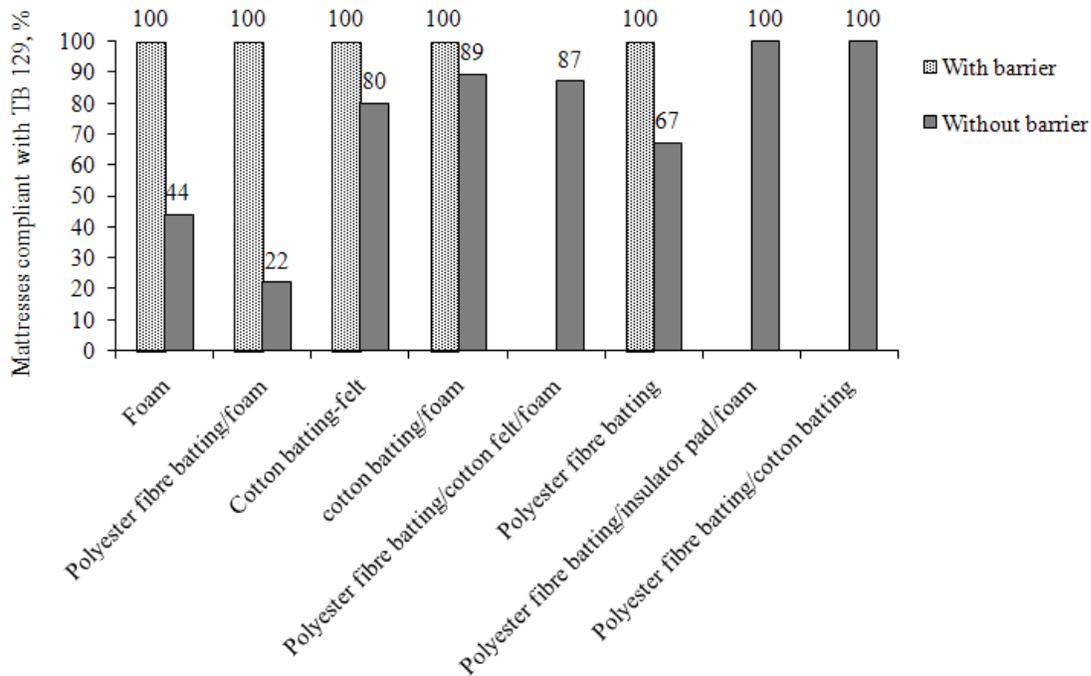


Figure 3. Comparison of innerspring mattresses with different types of filling materials in the presence or absence of BF [29].

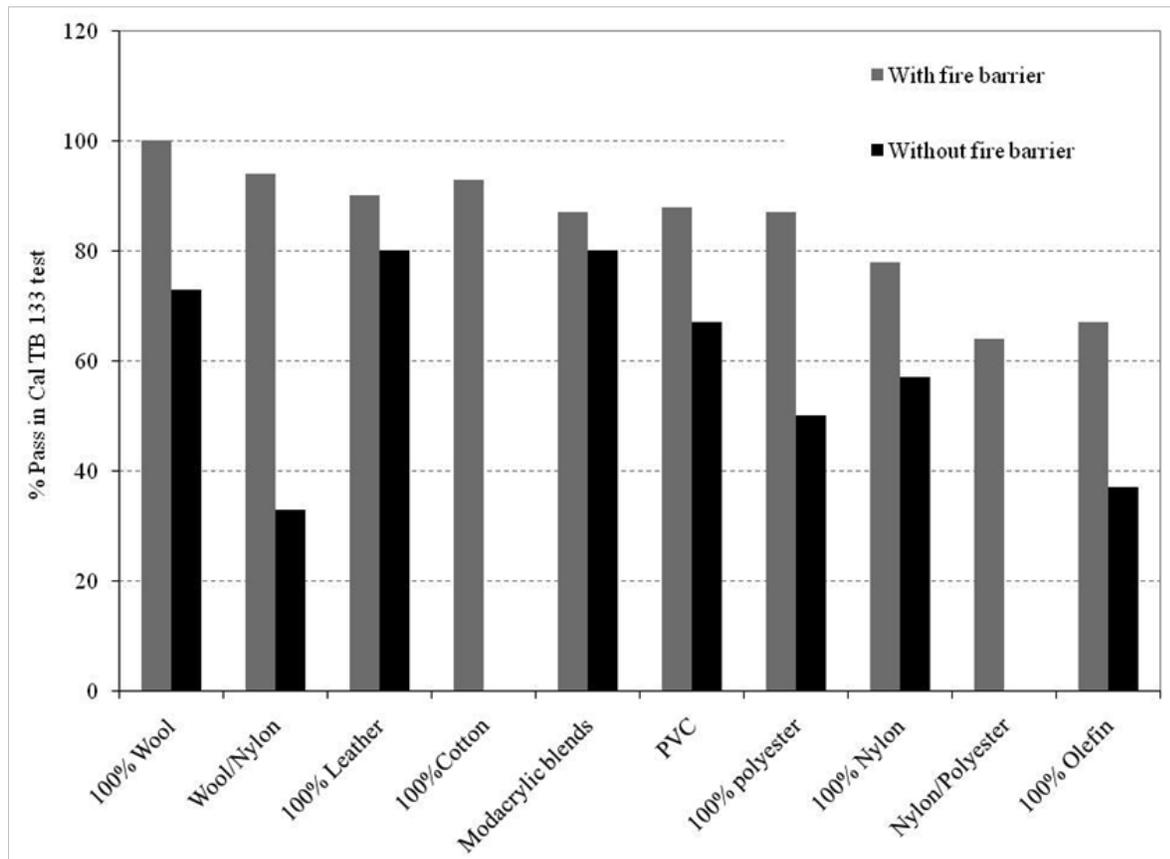


Figure 4. Impact of BF on Cal TB 133 test results [39].

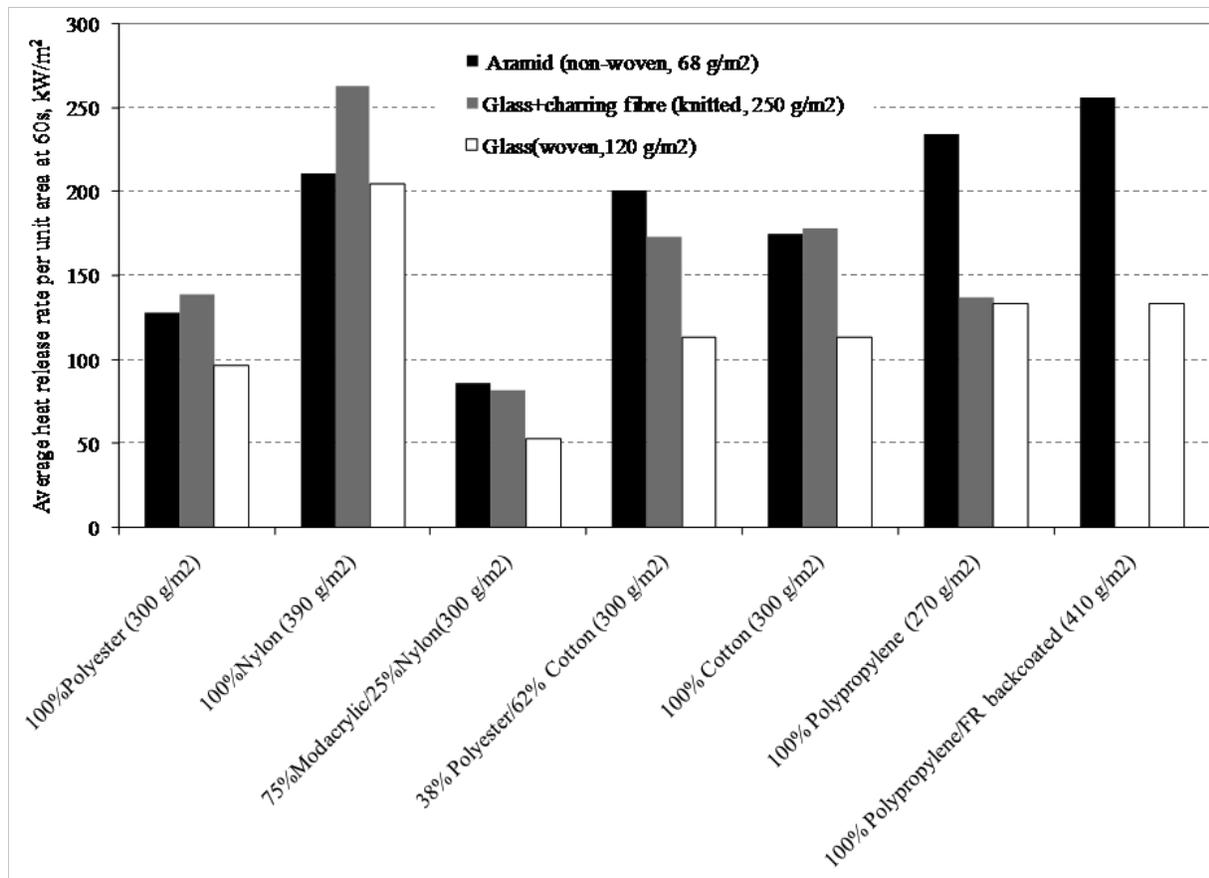


Figure 5. Impact of different cover fabrics and fire barriers on PHRR of composite specimens tested under cone calorimeter (35 kW/m^2) [13].



Figure 6. Meeker burner testing set up for studying char characteristics.

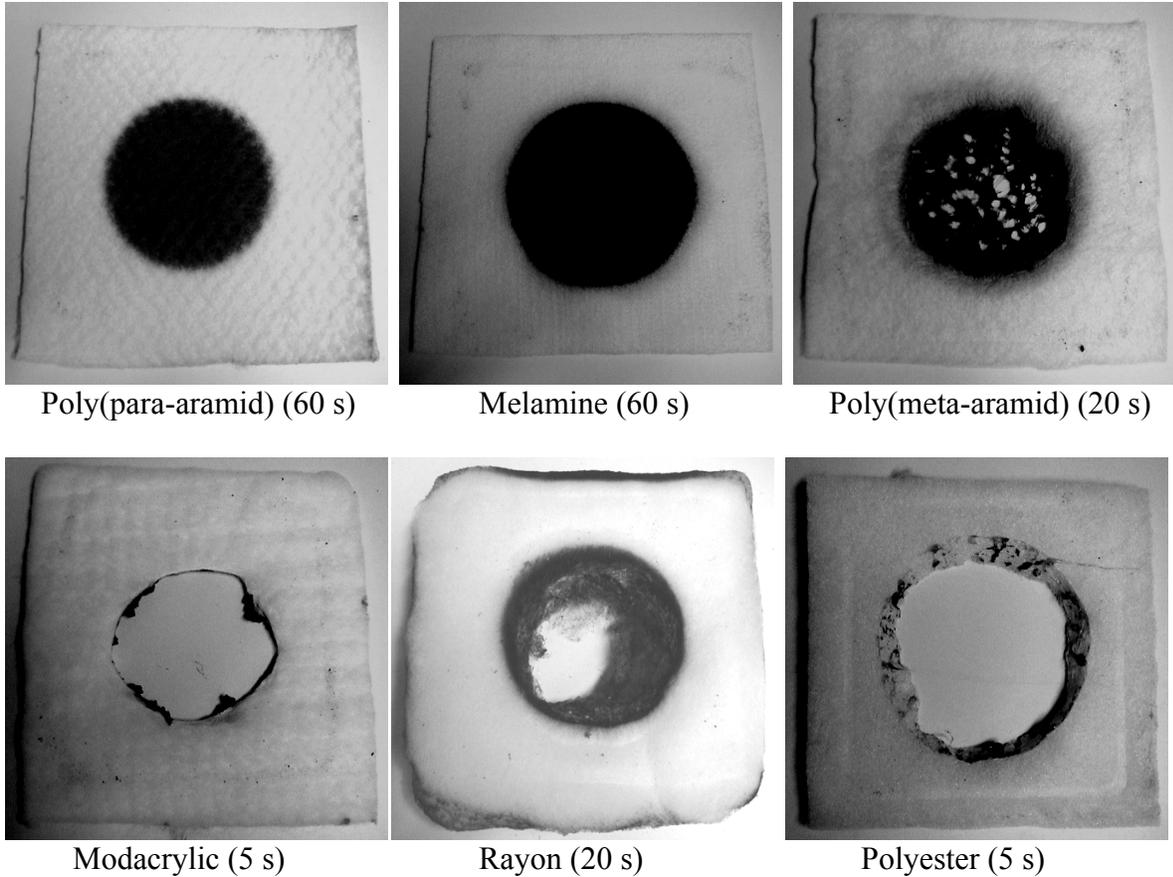


Figure 7. Char characteristics of nonwoven felts. Note: Values in parentheses show exposure time to open flame.

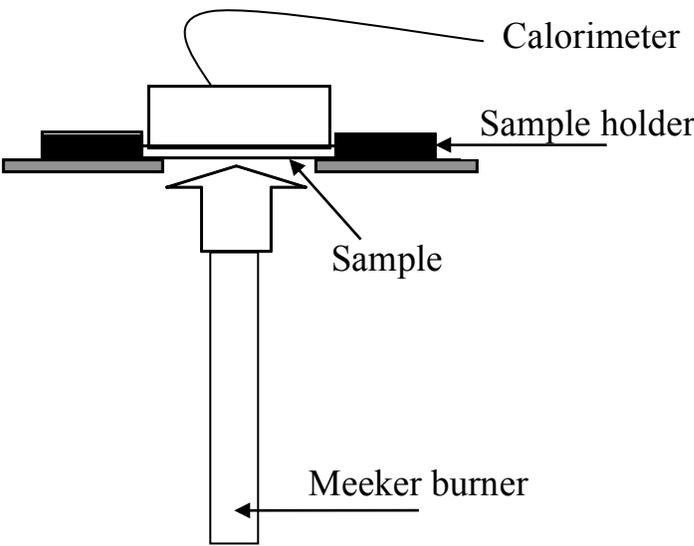


Figure 8. Schematic of ASTM D 7140 test method for barrier materials.

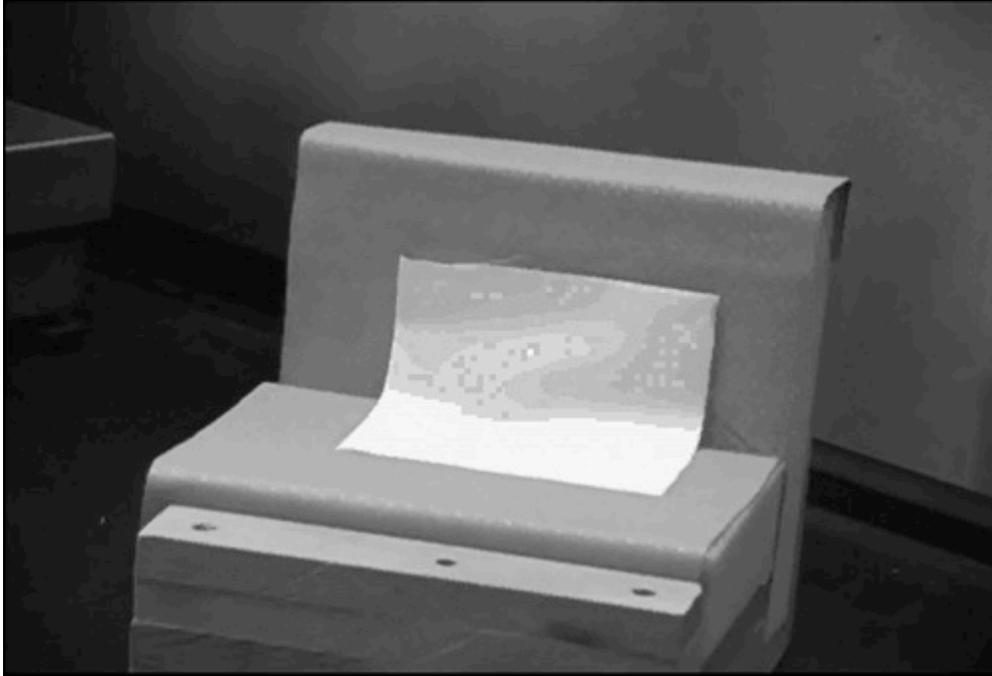


Figure 9. Mockup arrangement for UFAC smoldering ignition testing of BFUs used in upholstered furniture.

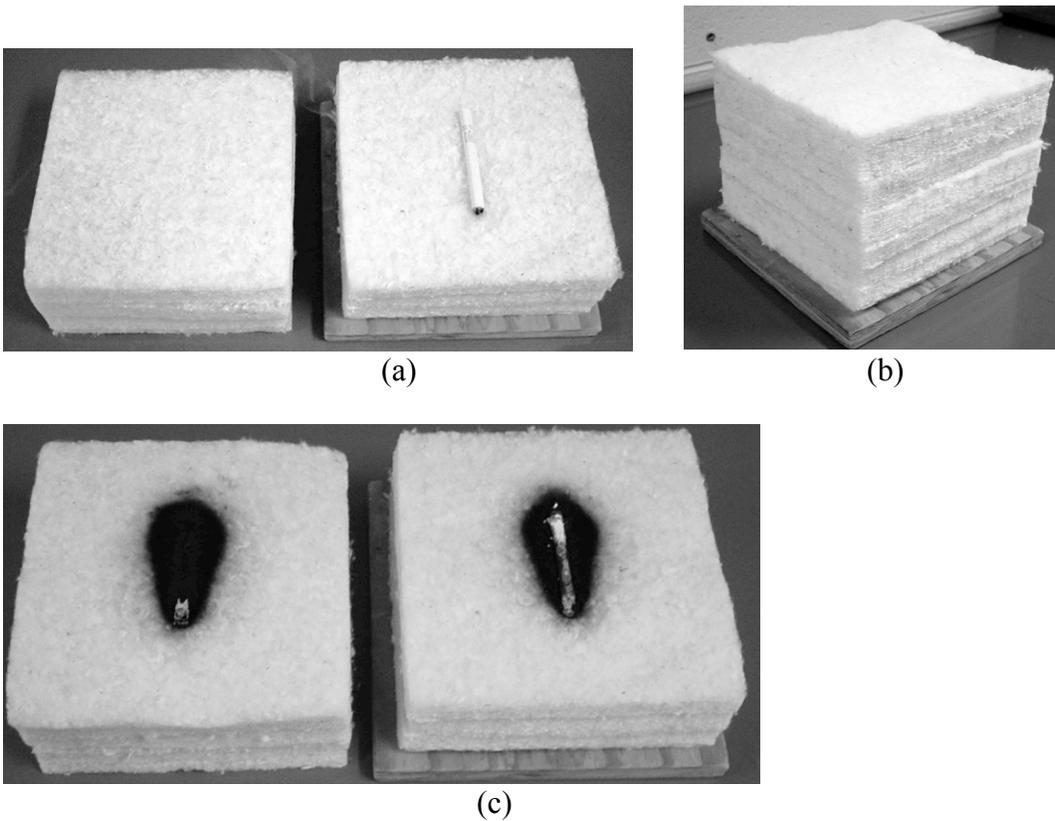


Figure 10. ASTM D 5238 test for smoldering ignition resistance of cotton batting: (a) start, (b) test in progress, and (c) end of the test. Cotton batting stack on left of (a) is placed on top of the cigarette/cotton batting stack on the right of (a) to form the testing setup in (b).



(a)



(b)

Figure 11. Modified Cal TB 117 for testing barrier flammability: (a) vertical and (b) horizontal configuration.

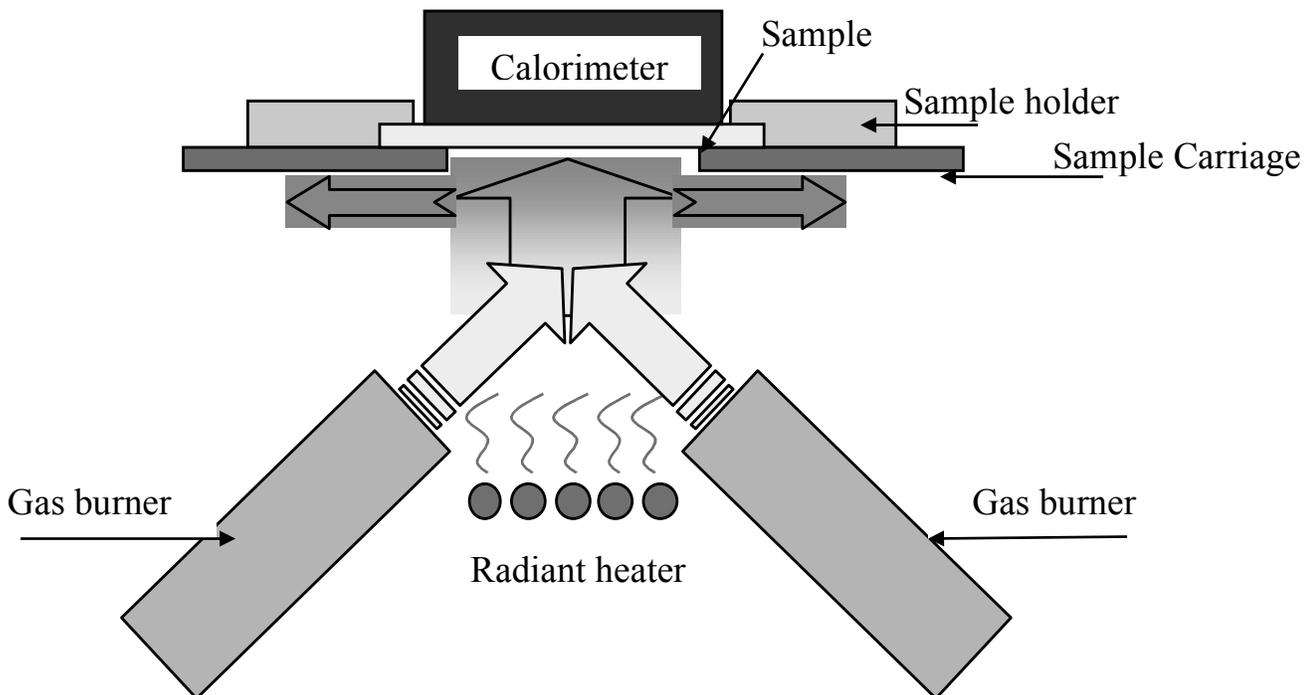


Figure 12. Schematic of TPP test device.

Table 1. Examples of commercially available BF for soft furnishings.

	Structure	Constituent fibers	Thickness, mm	Area density, g/m ²	Application
Non-woven	Thermally bonded highloft	FR rayon/polyester	10 to 15	150 to 250	Residential mattresses
		Basalt-based fiber/FR treated cotton/polyester			
	Needlepunched stratified	Inherent FR fibers	-	-	
	Needlepunched	FR Rayon/Polyester low melt synthetic fiber	-	225 to 245	
		Boric acid treated cotton	-		
	Needlepunched stratified	Boric acid treated cotton/ polyester fiber + FR rayon/polyester	-		
	Needlepunched Stitchbond	FR rayon/polyester	2 to 8	140 to 240	
0.9			180		
Needlepunched	FR rayon	-	-		
Non-woven	Glass fiber	10 to 11	230 to 260	Non-residential mattress	
Woven	Woven	Glass fiber	5 to 6	100 to 130	Upholstered furniture
		Core spun yarn with glass fiber core and FR modacrylic sheath	-	169.5	
Knitted	Knitted	Core spun yarn with glass fiber core and FR modacrylic sheath	-	186.45	
	Double face knit		-	237.3	

Table 2. Performance and properties of various cover fabrics in cigarette ignition and small open flame tests [42].

Sample description	Fiber content	Fabric construction	Area density, (g/m ²)	Cigarette ignition test	Small open flame test
Cover Fabric I	100 % FR Polyester	Plain weave	220	Not Tested	√/P
Cover Fabric II	100 % cotton	Twill	413	X	√/F
Cover Fabric III	100 % cotton	Pile weave corduroy	332	X	√/F
Cover Fabric IV	100 % Cotton	Plain weave	220	X	√/F
Cover Fabric V	56 %Rayon/34 %polyester/10 %cotton	Jacquard	349	X	√/F
Cover Fabric VI	60 % acetate/40 % cotton	taffeta	136	X	√/F
Cover Fabric VII	100 % silk	Plain weave	125	X	X
Cover Fabric VIII	57 % acrylic/31 %polyester/12 %olefin	Plain weave	303	X	√/F

X : no ignition, √/P: ignition but passes the test, √/F: ignites and fails the test.

Table 3. Performance of various BFs in cigarette ignition, small open flame, and wooden crib tests [42]. Not tested (grey), Pass (yellow), Failed (red), No ignition (X), Ignition (√).

BF description	Ignition source	Cover Fabric								
		None	I	II	III	IV	V	VI	VII	VIII
Cotton 100%, 220 g/m ²	Cigarette	X	X	√/Fail	X, √/Fail	X	X	X	X	X
	Butane flame	X	X	X	√/Pass	√/Pass	√/Fail, √/Pass	√/Pass, √/Fail	X	√/Fail
	Wooden crib	√/Fail	√/Fail							
Cotton 100%, 202 g/m ²	Cigarette	X	X	X	√/Fail	X	X	X	X	X
	Butane flame	X	X	X	√/Pass	√/Pass, √/Fail	√/Pass	√/Pass	X	√/Fail
	Wooden crib	√/Fail	√/Fail							
Cotton 100%, 237 g/m ²	Cigarette	X	X	X	√/Fail	X	X	X	X	X
	Butane flame	X	X	X	√/Pass	√/Pass	√/Pass, /Fail	√/Pass	X	√/Fail
	Wooden crib	√/Fail	√/Fail							
Aramid 100%, 102 g/m ²	Cigarette	X	X		√/Fail				X	
	Butane flame	X	X		√/Pass				X	√/Pass
	Wooden crib	√/Pass	√/Pass							
Melamine/aramid, 51 g/m ²	Cigarette	X	X	X	√/Fail	X	X	X		X
	Butane flame	√/Pass	√/Pass	√/Fail	√/Pass	√/Pass	√/Pass	√/Pass		√/Pass
	Wooden crib	√/Pass	√/Fail							
Melamine/aramid, 102 g/m ²	Cigarette	X	X	X	√/Fail	X	X	X		X
	Butane flame	√/Pass	√/Pass	√/Fail	√/Pass	√/Pass	√/Pass	√/Pass		√/Pass
	Wooden crib	√/Pass	√/Pass							
100% novoloid (phenol-aldehyde), 81 g/m ²	Cigarette									
	Butane flame	X								
	Wooden crib	√/Pass								
100% novoloid (phenol-aldehyde), 125 g/m ²	Cigarette	X	X	√/Fail	√/Fail	√/Fail	X	√/Fail		X
	Butane flame	X	X	√/Fail	√/Pass	√/Pass	√/Fail	√/Pass		√/Pass
	Wooden crib	√/Pass	√/Pass							
100% novoloid (phenol-aldehyde), 190 g/m ²	Cigarette									
	Butane flame	X								
	Wooden crib	√/Pass								
Melamine/modacrylic/polyester, 136 g/m ²	Cigarette	X	X	√/Fail	√/Fail	√/Fail, XX	X	X		X
	Butane flame	√/Pass	√/Pass	√/Fail	√/Fail	√/Pass	√/Fail	√/Pass		√/Pass
	Wooden crib	√/Pass	√/Pass							
Melamine/modacrylic/polyester, 475 g/m ²	Cigarette	X	X	√/Fail	X	X	X	X		X
	Butane flame	√/Pass	√/Pass	√/Fail	√/Pass	√/Fail	√/Fail	√/Pass		√/Pass
	Wooden crib	√/Pass	√/Pass							

6. References

- [1] Hall JR. Total cost of fire in the United States. National Fire Protection Association; February (2008). Summary available from:
<http://www.nfpa.org/assets/files/PDF/totalcostsum.pdf>.
- [2] Hall JR, Harwood B. The national estimates approach to U.S. fire statistics. *Fire Tech.* 25(2) (1989) 99-113.
- [3] Greene M, Miller D. 2006-2008 Residential Fire Loss Estimates. Consumer Product Safety Commission report. August (2010). Available from:
<http://www.cpsc.gov/library/fire06.pdf>.
- [4] Ahrens M. Home fires that began with upholstered furniture. National Fire Protection Association. May (2008). Summary available from:
<http://www.nfpa.org/assets/files/PDF/UpholsteredExecutiveSum.pdf>.
- [5] Technical Bulletin 129: Flammability Test Procedure for Mattresses for Use in Public Buildings, October 1992, State of California Department of Consumer Affairs Bureau of Home Furnishings and Thermal Insulation 3485 Orange Grove Avenue North Highlands, CA 95660-5595. <http://www.bhfti.ca.gov/industry/bulletin.shtml>
- [6] California TB 603, Requirements and Test Procedure for Resistance of a Residential Mattress/Box Springs Set to a Large Open- Flame, Now replaced by 16CFR 1633.
- [7] Technical Bulletin 133: Flammability Test Procedure for Seating Furniture for Use in Public Occupancies, January 1991 State of California Department of Consumer Affairs Bureau of Home Furnishings and Thermal Insulation 3485 Orange Grove Avenue North Highlands, CA 95660-5595.
- [8] 16 CFR 1633 Standard for the flammability (open flame) of mattress sets. Consumer Product Safety Commission. March (2007). Available from:
<http://www.cpsc.gov/businfo/frnotices/fr06/mattsets.pdf>.
- [9] 16 CFR Part 1634, Standard for the flammability of residential upholstered furniture (proposed rule). Consumer Product Safety Commission. March (2008). Available from:
<http://www.cpsc.gov/businfo/frnotices/fr08/furnflamm.pdf>.
- [10] European Union, "Registration, Evaluation, Authorization and Restriction of Chemicals" (REACH), EC Reg. No 1907/2006 (2006), "Restriction of Hazardous Substances Directive (RoHS), Dir. 2002/95/EC (2003), "Waste Electrical and Electronic Equipment Directive" (WEEE) Dir. 2002/96/EC (2003).
- [11] Chivas C, Guillaume E, Sainrat A, Barbosa V. Assessment of risks and benefits in the use of flame retardants in upholstered furniture in continental Europe. *Fire Safety Journal.*2009; 44(5): 801-807.
- [12] Ohlemiller TJ and Gann RG. Estimating reduced fire risk resulting from an improved mattress flammability standard, NIST Technical Note 1446, August 2002. National Institute of Standards and Technology, Gaithersburg MD.
- [13] Ohlemiller TJ and Shields J. Behavior of mock-ups in the California Technical Bulletin 133 test protocol: Fabric and barrier effects, NISTIR 5653, May 1995, National Institute of Standards and Technology, Gaithersburg MD.
- [14] Ohlemiller TJ, Shields JR. Assessment of medium-scale, polyurethane foam flammability test, NIST Technical Note 1495, February 2008, National Institute of Standards and Technology, Gaithersburg MD.

-
- [15] Ohlemiller TJ, On the Criteria for Smoldering Ignition in the CFR 1632 Cigarette Test for mattresses, NIST Technical Note 1601, November 2008, National Institute of Standards and Technology, Gaithersburg MD.
- [16] Ohlemiller TJ, Shields JR, McLane RA, Gann RG. Flammability assessment methodology for mattresses, NISTIR 6497, June 2000, National Institute of Standards and Technology, Gaithersburg MD.
- [17] Gann RG, et al., Upholstered furniture flammability research: A review of recent publications, NIST Technical Note in preparation, National Institute of Standards and Technology, Gaithersburg, MD, 2011.
- [18] Reduced risk of furniture fire hazard, http://www.nist.gov/el/fire_protection/buildings/reduced_risk_of_furniture_fire_hazard.cfm, viewed on 6/1/11.
- [19] Horrocks AR, Kandola B, Padmore K, Dalton J, Owen T. Comparison of cone and OSU calorimetric techniques to assess the flammability behavior of fabrics used for aircraft interiors. Proceedings of the 7th Fire and Materials Conference, San Francisco, U.S.A., 22-24th January 2001; 231.
- [20] Paul KT, Reimann KA, and Sundstorm B, Furniture and Furnishings, Chapter 13 in Plastics flammability handbook: principles, regulations, testing, and approval. Troitzsch J. (Editor), Hanser Publishing, 2004.
- [21] Krämer RH, Zammarano M, Linteris GT, Gedde UW, Gilman JW. Heat release and structural collapse of flexible polyurethane foam, *Polymer Degradation and Stability*, Volume 95, Issue 6, June 2010, Pages 1115-1122.
- [22] Chattopadhyay DK, Webster DC. Thermal stability and flame retardancy of polyurethanes *Progress in Polymer Science*. 2009;34(10):1068-1133.
- [23] Lefebvre J, Bastin B, Le Bras M, Duquesne S, Ritter C, Paleja R, Poutch F. Flame spread of flexible polyurethane foam: comprehensive study. *Polymer Testing*. 2004;23(3):281-290.
- [24] Levchik SV, Weil ED. Thermal decomposition, combustion and fire-retardancy of polyurethanes - a review of the recent literature. *Polymer International*. 2004;53(11):1585-1610.
- [25] Ohlemiller TJ. A study of size effects in the fire performance of beds, NIST TN 1465, January 2005, National Institute of Standards and Technology, Gaithersburg MD.
- [26] 16 CFR 1632 Standard for the flammability (Cigarette ignition) of mattress and mattress pads. Consumer Product Safety Commission. May (1991). Available from: www.cpsc.gov/businfo/regsummattress.pdf
- [27] Ohlemiller TJ and Gann RG. Effect of bed clothes modifications on fire performance of bed assemblies, NIST Technical Note 1449, February 2003, National Institute of Standards and Technology, Gaithersburg MD.
- [28] California TB 121 - Flammability Test Procedure for Mattresses for Use in High Risk Occupancies, April 180, State of California Department of Consumer Affairs Bureau of Home Furnishings and Thermal Insulation, 3485 Orange Grove Avenue, North Highlands, California 95660-5595 <http://www.bhfti.ca.gov/industry/bulletin.shtml>
- [29] Nurbakhsh S, Mc Cormack J. A review of the Technical Bulletin 129 full scale test method for flammability of mattresses for public occupancies. *Journal of Fire Sciences*, 1998;16:105-124.

-
- [30] Nazare S, Davis R. Assessment of factors affecting fire performance of mattresses: A review, NIST Technical Note in preparation, National Institute of Standards and Technology, Gaithersburg, MD, 2011.
- [31] Damant GH, Nurbakhsh S. Heat release tests of mattresses and bedding systems. *Journal of Fire Sciences*. 1992; 10: 386 - 410.
- [32] Ticking Trends: Suppliers cope with fast-changing demands, Featured Article in *BedTimes*, October 2005,
<http://www.bedtimesmagazine.com/Articles/2005/October/TickingTrends.html>
- [33] Fritz TW and Hunsberger PL. Testing of mattress composites in the cone calorimeter, *Fire and Materials*. 1997; 21:17-22.
- [34] Sundström B, (Editor). *Fire Safety of Upholstered Furniture-The final report on the Combustion Behavior of Upholstered Furniture (CBUF) Program*, June 1995, Interscience Communications Ltd.
- [35] ASTM E 1537-07 Standard Test Method for Fire Testing of Upholstered Furniture.
- [36] BS 5852:2006 Methods of test for assessment of the ignitability of upholstered seating by smoldering and flaming ignition sources.
- [37] FAA Oil burner test for aircraft seat cushions, part II of Appendix F Title 14 Code of Federal Aviation Regulation (CFR) Part 25.853. November 26, 1987.
- [38] Grand AF, Priest DN and Stansberry HW. Burning characteristics of upholstered chairs, Fire and flammability of furnishings and contents of buildings, ASTM STP 1233, Fowell AJ, Editor, American Society for Testing materials, Philadelphia, 1994, pp. 63-82.
- [39] Damant GH and Nurbakhsh S. Using California Technical Bulletin 133 to measure heat release rate tests of seating furniture, in *Fire and Flammability of Furnishings and Contents of Buildings*, Fowell A.J. (Editor), ASTM Publication, Philadelphia, USA, 83-97, (1994).
- [40] Forsten HH. Cone calorimeter studies of furniture component system, in *Fire and Flammability of Furnishings and Contents of Buildings*, Fowell A. J. (Editor), ASTM Publication, Philadelphia, USA, 105-113, (1994).
- [41] Damant GH, Williams SS and McCormack JA. The role of fabric in the cigarette ignition of upholstered furniture, *Journal of Fire Sciences*. 1983; 1: 309-320.
- [42] Memorandum to D. Ray from Linda Fansler, Exploratory test of barrier materials, October 2004, Consumer Product Safety Commission, Washington DC.
- [43] Damant GH. Use of barriers and fire blocking layers to comply with full-scale fire tests for furnishings. *Journal of Fire Sciences*. 1996;14:3 - 25.
- [44] Coles AR. Flammability of upholstered furniture using the cone calorimeter. M.E. (Fire) Degree Thesis, University of Canterbury, New Zealand, 2000.
- [45] Damant GH. Cigarette ignition of upholstered furniture. *Journal of Fire Sciences*. 1995; 13:337 - 349.
- [46] Damant GH, *Fire Barriers for Furnishings – Overview and Early History*, Presented at NIST Fire Barrier Workshop, March 18 – 19, 2009.
- [47] Wakelyn PJ, Adair PK, Barker RH. Do open flame ignition resistance treatments for cellulosic and cellulosic blend fabrics also reduce cigarette ignitions? *Fire and Materials*. 2005; 29:15–26.
- [48] Schumann JG, Hartzell GE. Flaming combustion characteristics of upholstered furniture. *Journal of Fire Sciences*. 1989;7: 386 - 402.

-
- [49] Damant GH. Flammability of furnishings: Someone had to be first!, In conference Proceedings of the Flame retardants '90 Conference, Queen Elizabeth II Conference Centre, Westminster, London, UK, 17-18, January 1994, pp.242-264.
- [50] Eggestad J, Johnsen AC. Effects of interliners on the ignitability of upholstered furniture, *Journal of Fire Sciences*. 1987; 5:152 - 161.
- [51] Babrauskas V. Unexposed-face temperature criteria in fire resistance tests: A reappraisal. *Fire Safety Journal*. 2009; 44(6):813-818.
- [52] Horrocks AR. Developments in flame retardants for heat and fire resistant textiles—the role of char formation and intumescence, *Polymer Degradation and Stability*. 1996;54(2-3):143-154.
- [53] Bourbigot S, Flambard X. Heat resistance and flammability of high performance fibres: A review, *Fire and Materials*. 2002; 26 (4-5):155-168.
- [54] US Patent Application 20070161312 - Fiberglass fire barrier for mattresses. Filed on January 11, 2006. Published on [July 12, 2007](#).
- [55] Dry N. et al, Flame resistant matelasse fabrics. WIPO Patent Application WO/2006/116674 , Filed on April 28, 2006. Published on [November 02, 2006](#).
- [56] Dennis M L and Handermann AC. Nonwoven highloft flame barrier. Application number 10/474395, Filed on 09/11/2002. Published on 08/21/2007.
- [57] <http://www.alessandrayarns.com/about.html>
- [58] Anon, Fire barrier technologies. Available at: <http://www.frsystems.ca/firebarrier.html>
- [59] Gallagher JA. Interliner effect on the fire performance of upholstery materials. *Journal of Fire Sciences*. 1993;11:87-105.
- [60] Weil ED, Levchik SV. Flame retardants in commercial use or development for textiles. *Journal of Fire Sciences*. 2008; 26: 243 - 281.
- [61] Nazare S. Sustainable 'Environmentally Friendly' Flame Retardant Textiles. Chapter 14 in *Sustainable Textiles*, R. Blackburn (Editor), Woodhead Publishing Ltd. Cambridge, UK (2009).
- [62] Decabromodiphenylether: An Investigation of non-halogen substitutes in electronic enclosure and textile applications, (2005), Publication of the Lowell Centre for Sustainable Production, MA, USA.
- [63] Small JD, Walton JH. US Patent Application US 2007 141,938.
- [64] Ma X, Multilayered fire blocking fabric structure having augmented fire blocking performance., US Patent Application US 2007 99,533.
- [65] Parikh DV, Sachinvala ND, Sawhney APS, Robert KQ, Graves EE, Calamari TA, Chen Y, and Jirsak O. Flame Retardant Cotton Blend Highlofts, *Journal of Fire Sciences*. 2003;21:383 - 395.
- [66] Hendermann A, Bridges SA. Slickened or siliconised flame-resistant fiber blends and flame barrier, US Patent Application, US 2006 160,454.
- [67] Weil ED ,Yang C. Textile flame retardancy-State of art and recent progress, 19th Annual BCC Conference on Flame Retardancy, BCC Communications, 9-11 June 2008, Stamford, Connecticut.
- [68] Shanley LA, Slaten BL, Shanley P, Broughton R, Hall D, Baginski M. Thermal properties of novel carbonaceous fiber battings. *Journal of Fire Sciences*. 1994;12: 238 - 245.

-
- [69] Mater DL., Handermann AC., Nonwoven highloft barrier, US Patent Application, US 7259117, 2007.
- [70] Hendermann AC. Flame resistant barriers for home furnishings. *Journal of Industrial Textiles*. 2004; 33(3):159-178.
- [71] Horrocks AR, Anand SC, Sanderson D. Fiber-intumescent interactive systems for barrier fabrics. In conference Proceedings of the Flame retardants '94 Conference, Queen Elizabeth II Conference Centre, Westminster, London, UK, 26-27th January 1994, pp. 117-128.
- [72] Flambard X, Bourbigot S, Ferreira M, Vermeulen B, Poutch F. Wool/para-aramid fibers blended in spun yarns as heat and fire resistant fabrics. *Polymer Degradation and Stability*. 2002; 77(2):279-284.
- [73] Kozlowski R, Mieleniak B, Muzyczek M, Kubacki A. Flexible fire barriers based on natural nonwoven textiles. *Fire and Materials*. 2002;26(4):243-246.
- [74] Kozlowski R, Mieleniak B, Muzyczek M. Fire resistant composites for upholstery. *Polymer Degradation and Stability*. 1999; 64(3):511-515.
- [75] Flambard X, Bourbigot S, Kozlowski R, Muzyczek M, Mieleniak B, Ferreira M, Vermeulen B, Poutch F. Progress in safety, flame retardant textiles and flexible fire barriers for seats in transportation. *Polymer Degradation and Stability*. 2005; 88(1):98-105.
- [76] Knoff WF, Hall W. Flame resistant fabric useful as a batting in mattresses and upholstery, US Patent Application US 2006 172,649.
- [77] Dombrowski R. Flame retardants for textile coatings, *Journal of Coated Fabrics*. 1996;25:224-238.
- [78] Toxicological Risks of Selected Flame Retardant Chemicals, National Research Council, National Academy of Sciences, US (2000).
- [79] Wakelyn PJ, Wolf S, Oliver K. Cotton batting fire-blocking barriers for soft furnishings. Presented at the 14th Annual Business Communications Company, Inc. (BCC) Conference on Flame Retardancy June 3, 2003. Stamford, CT.
- [80] Gandhi S, Spivak SM. A survey of upholstered furniture fabrics and implications for furniture flammability. *Journal of Fire Sciences*. 1994; 12:284 - 312.
- [81] Davis RD, Ohlemiller TJ, Steckler KD. Materials and fire performance testing of barrier fabrics in mattresses and upholstered furniture. *Fire and Materials*. 2009; 11th International Conference. Conference Papers. Proceedings. Organised by Interscience Communications Limited. January 26-28, 2009, San Francisco, CA, Interscience Communications Limited, London, England, 679-684 pp, 2009.
- [82] Horrocks AR, Anand SC and Sanderson D. Novel textile barrier fabrics which retain coherence and flexibility up to 900 deg C, In Conference Proceedings of the 6th International Interflam Conference. 1993; 689-698.
- [83] Kim YS, Davis RD, Cain AA and Grunlan JC. Development of layer-by-layer assembled carbon nanofiber-filled coatings to reduce polyurethane foam flammability, *Polymer*. 2011; 52: 2847-2855.
- [84] U.S. Environmental Protection Agency. 2010. DecaBDE Phase-out Initiative. Available: EPA.gov

-
- [85] Kemmlein S Herzke D, Law RJ. Brominated flame retardants in the European chemicals policy of REACH—Regulation and determination in materials. *Journal of Chromatography A*. 2009; 1216 (3): 320-333.
- [86] Singh H and Jain AK. Ignition, combustion, toxicity, and fire retardancy of polyurethane foams: A comprehensive review. *Journal of Applied Polymer Science*. 2009; 111(2): 111-1143.
- [87] Hashish F-Y, Hirsch D, Beeson H. Evaluation of polyimide foam as a fire barrier for spacecraft cushion materials. *Journal of Fire Sciences*. 2003; 21: 485 - 501.
- [88] Glossary of flexible Polyurethane foam technology, Joint Industry Foam Standards and Guidelines SECTION 15.0 Published: July 1994. Available from : <http://www.pfa.org/jifsg/jifsgs15.html>
- [89] ASTM D7140 - 07 Standard test method to measure heat transfer through textile thermal barrier materials.
- [90] Upholstery Furniture Action Council, UFAC Central Box 2436 High Point, NC 27261 <http://www.ufac.org/method1.htm>
- [91] ASTM D5238 – 10 Standard test method for smoldering combustion potential of cotton-based batting.
- [92] California TB 116, Requirements, Test Procedure and Apparatus for Testing the Flame Retardance of Upholstered Furniture.
- [93] California TB 117, Requirements, Test Procedures and Apparatus for Testing the Flame Retardance of Resilient Filling Materials Used in Upholstered Furniture.
- [94] ASTM D2863-00: Standard method for measuring the minimum oxygen concentration to support candle-like combustion of plastics (oxygen index).
- [95] Horrocks AR, Tunc M, Price D. The burning behavior of textiles and its assessment by oxygen-index methods. *Textile Progress*, Ed. L. Cegiela. 1989;18(1/2/3)
- [96] Nazare S and Horrocks AR, Flammability Testing, Chapter 11 in *Fabric Testing*, J. Hu (Editor), Woodhead Publishing Ltd. Cambridge, UK (2008).
- [97] Kandola BK, Horrocks AR. Complex char formation in flame-retarded fiber-intumescent combinations - IV. Mass loss and thermal barrier properties. *Fire and Materials*. 2000; 24,(6): 265-275.
- [98] Lawson JR and Pinder TA, Estimates of thermal conductivity for materials used in fire fighter's protective clothing, NISTIR 6512, May 2000.
- [99] ASTM D4108- Standard test method for thermal protective performance of materials for clothing by open-flame method.
- [100] ASTM D 737 - Standard test method for air permeability of textile fabrics.
- [101] http://echa.europa.eu/reach_en.asp
- [102] <http://ec.europa.eu/environment/ecolabel/>
- [103] <http://www.environmentalproductdeclarations.com/>
- [104] Wang MY, Horrocks AR, Horrocks S, Hall ME, Pearson JS, Clegg S. Flame retardant textile back-coatings. Part 1: Antimony-halogen system interactions and the effect of replacement by phosphorus-containing agents, *Journal of Fire Sciences*. 2000;18: 265 - 294.
- [105] Horrocks AR, Kandola BK, Davies PJ, Zhang S, Padbury SA. Developments in flame retardant textiles – a review. *Polymer Degradation and Stability*. 2005; 88(1): 3-12.

-
- [106] Horrocks AR, Davies PJ, Kandola BK, Alderson A. The potential for volatile phosphorus- containing flame retardants in textile back-coatings. *Journal of Fire Sciences*. 2007; 25:523 - 540.
- [107] Stevens GC, Horrocks AR. Textile back-coating environmental challenges for the UK furnishing fabrics industry: Release and exposure of flame retardant species. *Journal of Industrial Textiles*. 2003;32:267-278.
- [108] Rahatekar SS, Rasheed A, Jain R, Zammarano M, Koziol KK, Windle AH, Gilman JW, Kumar S. Solution spinning of cellulose carbon nanotube composites using room temperature ionic liquids. *Polymer*. 2009; 50(19):4577-4583.
- [109] Jain R, Liu Y, Rasheed A, Chae H, Gi, Kumar S. Polymer/carbon nanotubes composite fibers for fire barrier application. Annual Technical Report, April 2008, NIST (US Department of Commerce) Award Number: 70NANB6H6014.
- [110] Davis RD, Kim YS. Fabrication, characterization and flammability testing of carbon nanofiber layer-by-layer coated polyurethane foam, NIST TN 1674, September 2010.
- [111] Davis RD, Kim YS. Fabrication, Characterization and flammability testing of multi-walled carbon nanotube layer-by-layer coated polyurethane foam, NIST TN 1676, October 2010.