UNDERWRITERS LABORATORIES INC.

UL 118F

Managing Fire and Chemical Exposure Risks of Residential Upholstered Furniture

Managing Fire and Chemical Exposure Risks of Residential Upholstered Furniture, UL 118F

First Edition, Dated April 19, 2021

SUMMARY OF TOPICS

This First Edition of UL 118F, Managing Fire and Chemical Exposure Risks of Residential Upholstered Furniture has been published.

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PREFACE

Ongoing research, market awareness, and policy updates are recognizing the converging hazards of residential fires and human health impacts of flame retardant exposure. Residential upholstered furniture can contribute to home fires leading to deaths; yet the use of chemical flame retardants, to reduce fire hazards, can present adverse human health concerns. Research data shows that managing fire hazards and chemical exposure risks do not need to be mutually exclusive. Steps can be taken to design and select residential furniture that minimizes both risks and make safer products available for consumers and our indoor environments.

To address this issue, discussions and reviews were facilitated among an expert volunteer group, known as the Furniture Flammability and Human Health Taskforce, consisting of public health advocates, environmentalists, designers, fire experts, chemical and furniture material suppliers, and chemical exposure experts. The Taskforce was instrumental in bringing the science forward and summarizing key facts and action steps that can be taken to design and specify upholstered residential furniture with reduced flammability and chemical exposure risks.

Chemical Insights of Underwriters Laboratories Inc. was pleased to join with the Sustainable Furnishings Council to bring you this Guidance Document.

The following volunteers are acknowledged for their participation in this open and engaging dialogue and documentation:

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Introduction and Purpose

Furniture Flammability and Human Health (FFHH) Taskforce

Residential upholstered furniture is a significant component to any residential interior, adding function, comfort, and style to any household; but it can also be a contributor to residential fires that result in deaths.[1]

Some manufacturers have added chemicals, including flame retardants, to furniture materials to provide fire protection and improve other properties, but this may increase the risk of exposure to chemicals of concern. Fortunately, managing fire hazards and chemical risks do not need to be mutually exclusive. These guidelines (The Guide) present an evidence-based set of actionable guidelines to help interior designers and consumers specify and select residential upholstered furniture with reduced chemical flame retardant exposure and increased fire risk protection. It includes three sections:

Section 1: Designing Furniture for Minimizing Fire and Chemical Flame Retardant Risks

Section 2: Facts on Residential Fires and Flame Retardants

Section 3: Measuring Residential Upholstered Furniture Flammability and Exposure to Flame Retardant Chemicals

The Guide was derived from available scientific resources that were reviewed by the Furniture Flammability and Human Health (FFHH) Taskforce and summarized to share facts and information to designers and consumers on residential fires and flame retardant exposure. The Taskforce consisted of voluntary stakeholders including the furniture industry, material suppliers, chemical suppliers, designers, fire experts, chemical exposure experts, and public health advocates. More complete details of these reviews are provided in Sections 2 and 3 of this Guide. Topics included fire management processes, the use of flame retardants and other mitigation strategies, available fire test methods for evaluating fire prevention and mitigation impact, available methods for measuring flame retardants and other chemicals, and assessing human exposure risks. The intent is to educate and convey the science by optimizing solutions for minimizing fire hazards and chemical flame retardant risks associated with residential upholstered furniture use in indoor environments. The Guide was used to develop a “toolkit” so that consumers, designers, and specifiers do not have to choose one safety over the other.

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1 Designing Furniture for Minimizing Fire and Chemical Flame Retardant Risks

1.1 Overview

Residential upholstered furniture is a significant addition to any residential interior, with a life expectancy that may extend beyond 20 years. It is estimated that 10-50% of the cost of a home is spent on furniture. This is a significant financial investment for homeowners, and thus, good selections are essential.

Designing residential upholstered furniture for minimizing fire hazards and chemical risks requires optimizing design, material selection, and construction of the furniture (see Figure 1). Residential upholstered furniture acts as a fuel source when smoldering or open flame combustion occurs, making it a factor in fires and the unintentional death and injury rates associated with residential structure fires.[1] Flame retardants have been used to meet regulations intended to prevent smoldering or ignition or reduce the fire growth after ignition.[2,3] Because of health concerns and increasing regulations, there is movement, however, among U.S. furniture manufacturers to remove chemical flame retardants from material formulations. Some states and cities have taken action to regulate flame retardants, although the scope of specific flame retardants and applicable products vary among jurisdictions.[4]

Protection from fire hazards and chemical risks are not mutually exclusive, and it should be an essential safety feature of residential furniture. Studies show that certain fire mitigation strategies are available that do not require the addition of common flame retardants to minimize fire risks. Solutions include:[5,6]

- **Using a fire barrier material and no chemical flame retardants.** As an alternative to adding flame retardants, a physical fire barrier material can be used between the cover textile and the padding. This approach improves fire protection by preventing or slowing smoldering or ignition. Selection of barriers requires a good fabric hand.[7] Fabric hand is the assessment of the quality of the fabric specific to the function for factors of flexibility, rigidity, and softness, allowing it to be wrapped around resilient materials that may need additional protection to reduce flammability. These fire barriers may be made from a variety of fibers.

- **Excluding chemical flame retardants.** With careful material selection, furniture may be designed to resist cigarette smoldering hazards and to pass CA TB 117-2013 for verification without the use of flame retardants. This test method is not intended to measure performance of upholstered furniture under conditions of open flame exposure and does not indicate whether the furniture will resist ignition and the propagation when exposed to a flame.[8] Meeting this test standard may not protect the end-user from open flame hazards of furniture in residential fires.

There are other solutions available where fire hazards and chemical flame retardant risks are not jointly optimized for safety. In these cases, one element of safety has been prioritized over the other. These available approaches may have known human safety risks and are often used for compliance with product performance-based requirements. These solutions include:

- **Adding chemical flame retardants.** In situations where there are no regulations or defined requirements managing the use of added flame retardants, and if they are required by the end-user for specific situations, added flame retardants are used. Their use may be necessary to meet flammability standards in another countries, (i. e., UK) or in specialized environments. In these cases, expert advice should be obtained to advise on their use and to verify that all health and safety requirements are met. If chemical flame retardants are added, human exposure to these flame retardants is possible.[9,10]

- **Using alternative flame retardants.** Alternative flame retardants known as “reactive or polymeric” are becoming available in the marketplace. These chemically bind in polyurethane foam, a common padding used in furniture, and are not expected to be released into the indoor environment.[11] They improve fire protection by preventing or delaying flaming ignition. However, most of these alternative flame retardants are still proprietary in formulation and lacking detailed third party data on fire and human exposure risks.

There are other additional product attributes for consideration in furniture design beyond fire hazards and chemical risks protection. These include design aesthetics, sustainability, comfort and wellness, durability, life-cycle assessment, and costs. These additional features may increase the complexity for specification and purchasing residential upholstered furniture, but they may be important to end-users. This Guide focuses specifically on processes for optimizing fire and chemical flame retardant safety and does not consider these additional factors.

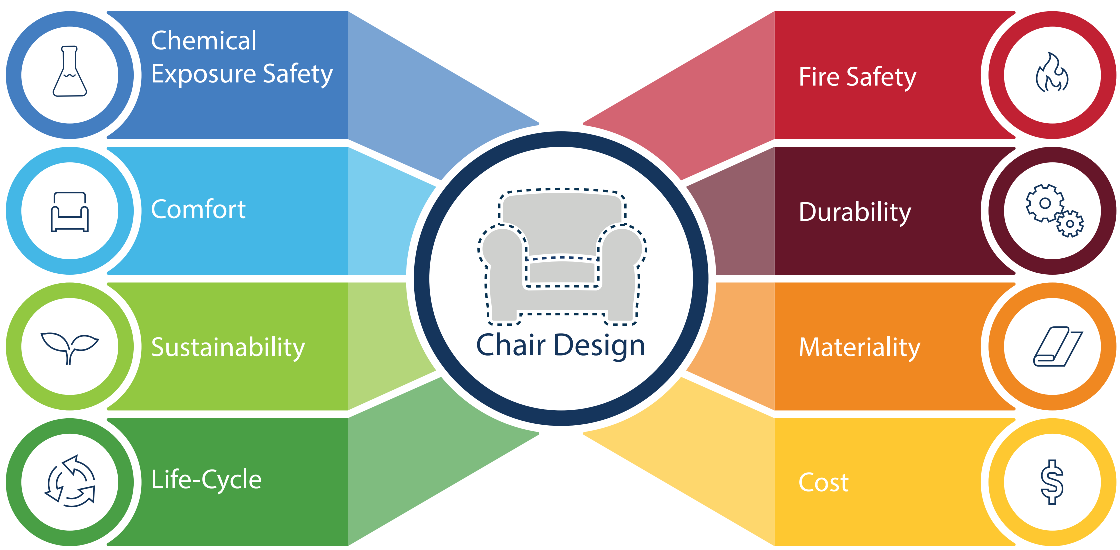


Figure 1

Product attributes for specification of residential upholstered furniture.

1.2 Summary of Fire and Chemical Risks

Specifiers and consumers benefit from transparency and understanding the choices provided by manufacturers in the upholstered furniture market. Decisions about health outcomes should not be a choice between fire hazards and chemical risks. Here are some important facts that specifiers and consumers should keep in mind:

Fire Hazards:

- Residential upholstered furniture contributes to approximately 22% of home fire deaths in the U.S.[12]

- Most residential upholstered furniture fire-related deaths occur when open flames are present and the fire spreads beyond the initial source.[12,13]

- Once the fire alarm (such as a smoke detector) sounds, residents may only have approximately two minutes to escape a home fire.[14]

Chemical Flame Retardant Use:

- Flame retardants may be added to residential upholstered furniture to meet fire performance requirements, decrease the ignitability of materials and/or inhibit the combustion process.

- There is no national regulation for managing the use of flame retardants nor for the mitigation of open flame hazards related to residential upholstered furniture.

- Some states have policies or regulations for prohibiting, limiting, or disclosing the use of flame retardants in residential upholstered furniture. Safer States, a diverse network of environmental health coalitions and organizations provides helpful information regarding state-adopted policies and can be found at https://saferstates.com/.

- Because of market demands and some state programs, U.S. manufacturers are shifting away from the use of flame retardants in material formulations.

Chemical Flame Retardant Health Concerns:

- Human exposure to flame retardants can occur via inhalation (breathing), ingestion (hand-to-mouth contact), or dermal transfer (surface to skin contact).

- Certain flame retardants can persist in the environment and bioaccumulate in people and wildlife.

- Some flame retardants in residential upholstered furniture have been found to be carcinogenic or have adverse human developmental effects like obesity, decreased memory and learning, decreased fertility, birth weight and sperm quality, and respiratory function.[15-17]

- Human exposure and health risks from the use of alternative reactive or polymeric flame retardants are not known.

Fire Risks Reduction Strategies:

- Material selection of upholstered furniture materials and components can help reduce fire risks.

- Using a fire barrier material between the furniture padding and cover textile can prevent or delay ignition of the upholstered furniture padding material.[6]

- Using tools such as sprinklers and fire extinguishers offer fire suppression of the environment.

- Fire alarms such as smoke detectors can be used to warn occupants and reduce the risk of injury and death from fires by early evacuation.

1.3 Material Selection

Flame-resistant materials may be used in residential upholstered furniture to slow and self-extinguish a fire, and reduce fire growth.[18] Material selection for upholstered furniture include textiles, fire barrier fabrics, resilient filling materials, structural framing, design components, and coatings and finishes (Figure 2). Each component of the chair may have multiple materials, such as a cover fabric, decking fabric, synthetic or natural fibrous padding, other resilient filling materials, framing, and exposed materials such as feet, arms, and trimming. Chemical-based flame retardants, coatings, and finishes may also be added before, during, or after fabrication of the furniture. Material selection should be based on criteria for aesthetics and comfort, but also for indoor environmental quality, and lessening fire hazards and chemical risks.

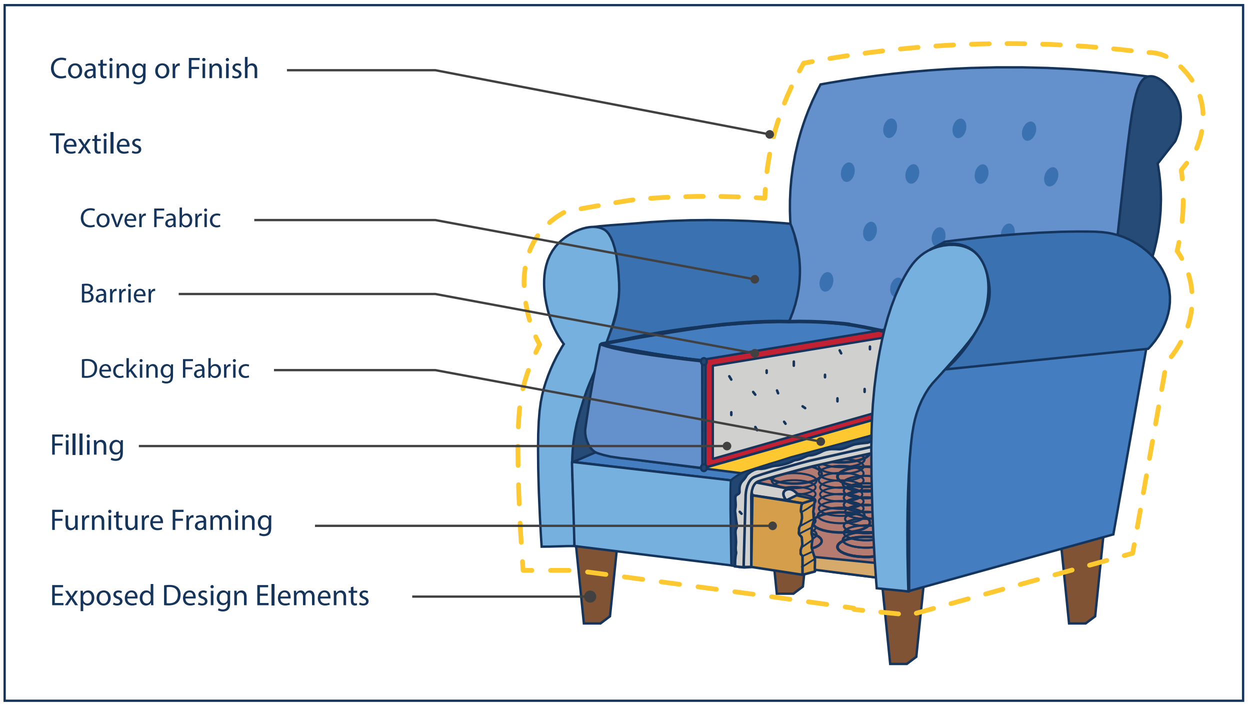


Figure 2

Common design components for specification of residential upholstered furniture.

1.3.1 **Textiles** can be classified as either natural or synthetic. Textiles used in residential upholstered furniture include cover fabric, barrier fabric and decking fabric.

• **Natural fibers.** Of the natural fibers, wool is the less flammable because it produces a high char yield so a large fraction of the material does not contribute to flaming combustion.[19] However, there are differences within wool depending on the breed, species, and characteristics of the textile construction.[20] Other natural fibers, such as cotton, linen, hemp, or rayon are more flammable and each have their own benefits and limitations for selection of upholstery fabric.

• **Leather.** Though heavily processed with added chemicals, leather has significant resistance to smoldering and flaming ignition.

• **Synthetic fibers.** Synthetic polymer fibers like acrylic, polyester, and nylon may have flame-resistant properties because of resistance to ignition at much higher temperatures than natural fibers, but may melt when the material burns, increasing risk of contact burning.[21] These fibers may contain flame retardants inherent in their chemistry.

• **High performance synthetics.** High performance upholstery textiles may be woven or nonwoven, made from a variety of synthetic fibers, and may have finishes and coatings applied to increase performance for soil and stain resistance, shrinkage control, bacteria resistance, ultraviolet (UV) resistance, moisture resistance, and flame resistance. Fiber examples include aramids, carbons, polyesters, and fiberglass. Coatings may be applied to increase durability, water resistance, conductivity control, and flame resistance; keep in mind that these coatings may be a source for unintentional off-gassing of chemicals with known adverse health effect.[22]

1.3.1.1 **Cover Fabrics** are the outermost layer of fabric or related material used to enclose the main support system, or the upholstery materials used in the furniture item.[8]

To address flammability and smoldering resistance, **back-coatings** may be applied to the backside of a cover fabric, sharing the same mechanisms of flame reduction discussed for fire barriers. Back-coatings can be classified as either active (acting by a combination of chemical and physical mechanisms and generally contain fire retardants) or passive (acting by physical mechanisms). Passive back-coatings can effectively combine flaming and smoldering ignition resistance in upholstery materials, rather than promoting smoldering ignition.[23,24]

1.3.1.2 **Decking Fabrics** are used to upholster the support under the seat cushion in a loose seat construction.[8] Decking fabrics may or may not have flame retardants added.

1.3.1.3 **Barriers** are used as a protective layer designed to prevent or delay ignition of the padding material to reduce the fire growth rate and the fire size after ignition.[25,26] A fire barrier is typically a fabric placed between the cover fabric and the padding or filling material. Fire barrier materials may be of various structures including knits and nonwovens[25] and may be of materials such as fiberglass[6,9] or a fabric that has been enhanced with flame retardants.

In studies comparing upholstered furniture constructed with a barrier and no flame retardants to the same upholstered chairs constructed using reactive flame retardants, or with a common added flame retardant, the chair with the fire barrier showed a significant decrease in heat release rate and ignition propensity.[6,27,28] Identification of a barrier that can delay or reduce open flames and pass the smolder resistance test is key. When selecting a barrier, the added cost per upholstered furniture item, including textile and increased fabrication cost to add the extra layer of protection, should be considered.

1.3.2 **Resilient Filling Materials** are cushioning materials in the form of batting, pads, or loose fills used in upholstered furniture. Back and seat cushions may be made of natural (e.g., feathers, latex foam, wool, or cotton) or synthetic loose fills (e.g., polyester) or foam made from polyurethane, natural materials, or a combination.

- **Loose filling** is often used in the back cushion and may be fabricated with natural or synthetic fibers and more commonly used in residential furniture for added comfort. Loose filling, depending on the material has a service life that varies and may need to be replaced over time.

- Lightweight outer **battings** are typically used to wrap foam cushions, to smooth the filling and to extend the life of the cover fabric. Higher density battings are used as filling to provide foundational support. Batting is typically made from cotton, wool, polyester, or a blend, and comes in various thicknesses, depending on the material. The type of batting selected will influence the feel and the life cycle of the finished product. Needled wool batting (wool felt) is strong and durable and may be used in foundation upholstery applications. Carded wool batting is a lightweight batting that can be used on the outside surface in place of lightweight polyester batting. When wool batting is used with a woven, non-coated cover fabric, a ticking fabric is required to prevent wool fibers from migrating through the weave to the surface of the cover fabric. Most common materials in use are a blend of cotton and polyester to combine the comfort and softness of cotton with the smoothness of polyester. A blend of cotton and wool imparts a similar result, with the added benefit of flame resistant properties of wool.

- **Foam padding** is specified based on performance criteria focused on comfort, support, and durability. Density contributes to comfort and support.

- **Polyurethane foams (PUF)** used in upholstered furniture remain one of the contributing factors for fire hazards in residential structure fires. Untreated polyurethane foams are combustible and prone to rapid fire growth due to their low density and low thermal conductivity.[29,30]

• A combination of textiles and foam specifications will influence the durability and flammability of the assembly. Foam with more density provides for physical stability which will increase the life of the cover textile. Foam density also plays a role as low density foams have more entrained air, reducing ignition resistance.

• Flame retardants added to the PUF are specifically designed and loaded to match the foam properties to extinguish some accidental fires and meet regulatory requirements.

• In recent years polymeric and reactive flame retardants have been proposed and used as a more stable alternative to conventional flame retardants. Reactive flame retardants are added during the manufacturing process of foaming, creating a material with inherent fire resistance properties.

1.3.3 **Upholstered Furniture Framing**

• **Hardwood.** In traditional upholstered furniture design, a kiln-dried hardwood frame represents quality design that ensures long-lasting durability. Poplar, alder, oak, maple, and ash are common wood types.

• **Engineered materials.** Engineered framing materials, such as 1-inch thick hardwood veneer plywood offers more flexibility for furniture design. Strand board and softwood plywood are other engineered wood materials used for framing. Wood framing uses a variety of traditional joinery methods supplemented with glued screwed joints.

• **Plywood and engineered wood materials** often include glues and finishes that can be a source of chemicals of concern released into the indoor environment.[31,32]

• **Other durable materials** for framing include steel, plastic, or a combination of materials. Furniture framed with metal or hardwood are not as flammable, however some residential upholstered furniture is framed with light wood or plastic, increasing flammability concerns.[33]

1.3.4 **Exposed design elements** like chair and sofa feet and exposed arms or trim are commonly made of wood or metal. A coating or finish may be applied to metal trim to protect the metal from corrosion. Wood elements may be paint grade or a variety of wood that is stain grade. It is not uncommon to have a stain and a lacquer finish applied. In some cases, a vinyl or other sealer for durability may be applied. Added flame retardants are not typically applied to exposed furniture components but focus on the polyurethane foam in residential upholstered furniture. To reduce fire hazards and chemical risks, specify metal or hardwood. When a finish or coating is necessary, specify finishes that are low volatile organic compounds (VOC) to limit chemical exposure risks, reducing potential health effects.[34-37]

1.3.5 Coatings and Finishes are added for a variety of reasons, including aesthetics, durability, moisture resistance, bacteria resistance, and flame resistance. Textile coatings and finishes may be applied on the face of the textile or on the backing, depending on the type of coating or finish and its function. Care should be taken to consider other chemicals as well as flame retardants including antimicrobials, polyvinyl chloride (PVC), polyfluoroalkyls (PFAS) and other chemicals with known health effects.

1.4 Best Practices for the Specification and Purchase of Residential Upholstered Furniture for Protection from Fire Hazards and Chemical Risks

Specifying and purchasing residential upholstered furniture can be complicated by prioritizing the reduction of risks associated with chemical exposures and fires. The following list includes recommendations for initial purchase; customization; refurbishment; cleaning, disinfecting, and decontaminating; and healthy material certification programs.

• **IDENTIFY** a strategy to achieve protection from fire hazards and chemical risks.

• **RECOGNIZE** and identify other desirable design attributes, such as sustainability, life cycle, and cost.

• **QUESTION** the information provided by the manufacturer, distributor, or retailer to make informed decisions. Ask:

o Where is this product manufactured?

o How is this product manufactured?

o What are the materials used in the fabrication of this product?

o Can the manufacturer/distributor/seller provide supply chain verification for each material composition in all components of the residential upholstered furniture, including chemicals used in the fabrication of all furniture components?

o Does the seller/distributor have documentation/chain of custody on special product attributes, i.e., Life Cycle Analysis (LCA), durability and comfort?

• **COLLECT** documentation for material review.

o Documentation for chemicals used in fabrication.

o Supply chain verification.

o Certifications and verifications for fire and chemical safety tests and special attributes.

o Manufacturer warranty and maintenance recommendations.

o Material Certification and Transparency Resources. The programs listed below provide acceptability information on chemical composition of materials for chemicals such as flame retardants and other coatings, and finishes used in upholstered furniture fabrication. There may be other credible third-party programs available:

▪ Cradle2Cradle – design framework for going beyond sustainability and designing for abundance in a circular economy: https://www.c2ccertified.org/

▪ International Living Future Institute's Declare – third-party verified transparency platform and product database: https://living-future.org/declare/declare-about/

▪ GreenScreen® For Safer Chemicals – an open, transparent, and publicly accessible method for chemical hazard assessment:
https://www.greenscreenchemicals.org/

▪ Health Product Declaration Collaborative (HPD) – a standard specification for accurate, reliable, and consistent reporting of product contents and associated health information: https://www.hpd-collaborative.org/

▪ mindful MATERIALS (mM) – this is an aggregator that brings together multiple third party certifications for healthy materials: http://www. mindfulmaterials. com/. mM Library: https://mindfulmaterials.origin.build/#/shared/materials/

▪ Sustainable Furnishings Council's The "What's it made of?" Initiative – focuses on improving supply chains to remove chemicals with known health concerns: https://sustainablefurnishings.org/content/whats-it-made-initiative

▪ UL GREENGUARD Certification Program – rigorous third-party chemical emissions standards to reduce indoor air pollution and the risk of chemical exposure: https://www.ul.com/services/greenguard-certification

▪ UL Product Lens™ Certification – exposure risk assessment of construction materials and hazard-based disclosures for complete chemical information in context: https://www.ul.com/resources/product-lens-certification-program

o Review resources for identifying chemical flame retardant health effects and risks:

▪ California Office of Environmental Health Hazard Assessment (OEHHA): Proposition 65 https://oehha.ca.gov/proposition-65/proposition-65-list

▪ CDC: Agency for Toxic Substances and Disease Registry (ATSDR) https://www.atsdr.cdc.gov/toxprofiledocs/index.html

▪ U.S. Department of Health and Human Services: National Toxicology Program (NTP) https://ntp.niehs.nih.gov/

▪ U.S. Environmental Protection Agency (EPA): Integrated Risk Information System (IRIS) https://iris.epa.gov/AtoZ/?list_type=alpha

• **SPECIFY** to minimize risks of chemical flame retardant exposure and fire. This includes specifying upholstered furniture with proven fire protection through validated independent testing. Tests that are available for validation include:

o Smoldering ignition resistant tests (pass CA TB 117-2013 or the European standard, EN 1201-1).

o Open flame tests (pass the European standard, EN 1201-2 or the British standard, BS-5852:2006)

o The flaming performance of upholstery material ensembles, that may include a barrier fabric, can also be assessed by the NIST developed Cube Test.[18]

• **SPECIFY** a barrier between the cover textile and the padding as a physical mechanism to delay ignition of the padding materials and reduce fire growth rate when flammable padding is used.

o The barrier should encapsulate the seat padding.

o When padding is added to the backing and armrest, the barrier should encapsulate the padding.

o Select materials low in volatile organic compounds (VOCs). GREENGUARD certification and other resources provide greater transparency when trying to understand potential chemical exposures.

• **SELECT** textiles and other furniture materials with inherent flame-resistant properties.

o The natural fibers of wool, silk, and leather are more difficult to ignite than synthetic fibers, burn slowly, and may self-extinguish. Cellulosic fibers such as cotton, linen, and rayon are easy to ignite with a smoldering source or with a small open flame.

o Fabrics made from synthetic fiber blends may or may not have flame retardants integral in the chemistry. Typical thermoplastic synthetic fabrics, such as polypropylene, nylon or polyester tend to melt.

o Using transparent resources, select materials with no chemicals of concern.

o Tests available for validating textile materials for smoldering and open flame include CA TB 117-2013 or the European standards, EN 1201-1, and EN 1021-2 or the British standard, BS-5852:2006)

o Select metal framing to reduce flammability. If metal is not available, consider selecting hardwood framing and avoid the soft woods common in the marketplace.

• **SUSTAIN** legacy furniture.

o Furniture with suspected or identified flame retardants or harmful chemicals, particularly those with known human health risks, should be reupholstered. Replace the textile, barrier, and padding with selections that meet the priority to reduce fire hazards and chemical risks.

o Continue to clean residential upholstered furniture including surface dust and floor dust around the furniture frequently with a HEPA vacuum and wash hands frequently.

2 Facts on Residential Fires and Flame Retardants

2.1 Background

While fire death rates have decreased in most countries worldwide since the 1980s, structural fire is still a threat. More than three million fires, 16.8 thousand civilian fire deaths, and 47.9 thousand civilian fire injuries were reported in 2017 among 34 countries representing 1.1 billion inhabitants (15% of the world's population).[38] During 2014-2018, U.S. fire departments responded to an estimated average of 353,100 home structure fires per year.[1] These fires caused an annual average of 11,030 civilian fire injuries; $7.2 billion in direct property damage; and 2,620 civilian fire deaths.[1] Most home fires and fire casualties result from five causes: cooking, heating, electrical distribution and lighting equipment, intentional fire setting, and smoking materials.[38] The U.S. has been successful reducing both the number of fires and fire deaths. However, the problem of preventing death in reported fires has not been solved. In 2019, the death rate per 1,000 fires was 8.2, or 14 percent higher than the 7.1 rate in 1980 (Figure 3a).[1] Roughly half of home fire deaths (49%) were caused by fires in just two rooms: living rooms and bedrooms (Figure 3b).[1] Fires in the living room were more likely to cause death than fires in other areas. The average death rate per 1,000 reported fires was roughly twice as high for fires that started in either the living room or bedroom in 2014-2018 compared to 1980-1984 (Figure 3c).[1] Upholstered furniture is the leading item first ignited when residential fire deaths are considered (Figure 3d) and the death rate from these fires has increased in the last 40 years (Figure 3e).[1] Residential upholstered furniture continues as a leading cause of residential fire deaths in the U.S. with the majority of these fires occuring when flaming is present and the fire spreads beyond the first item ignited.[1,13] Both the National Fire Protection Association (NFPA) and the American Red Cross report that people have only one to two minutes to escape a home once the fire alarm sounds.[14]

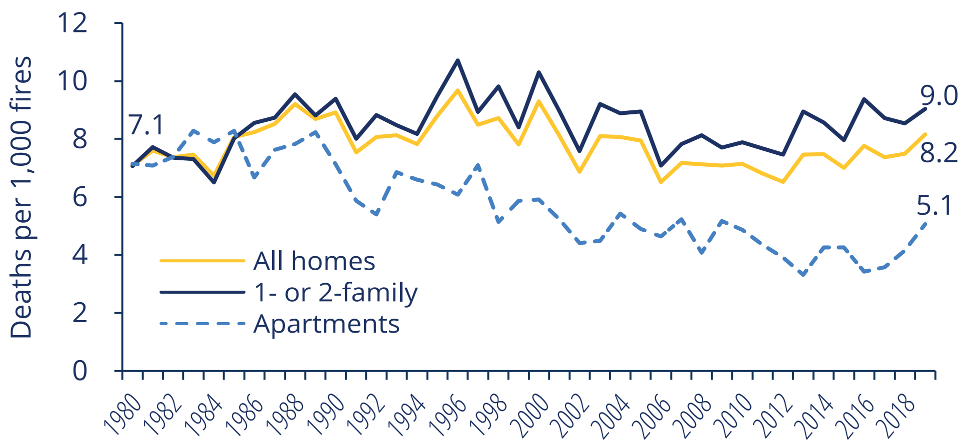
Other key facts include:

1. On average, one of every 12 reported residential upholstered furniture fires resulted in death.[39]

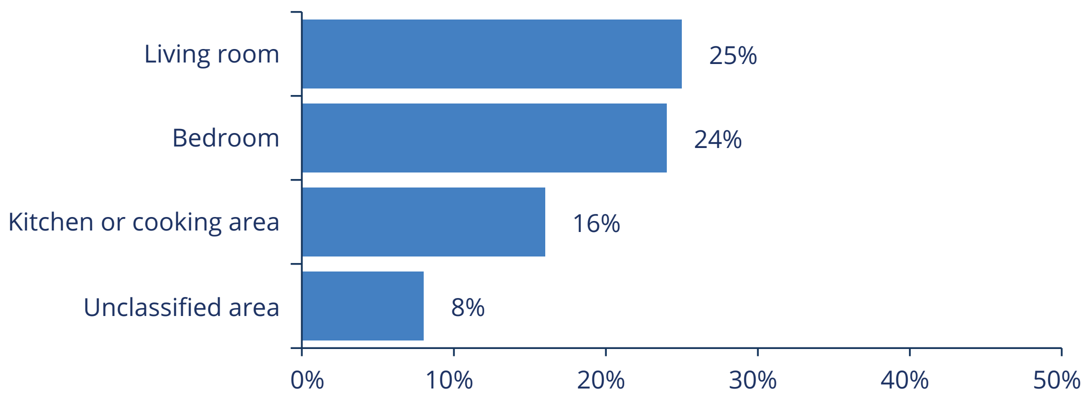
2. Ignition due to smoking materials is the most likely ignition source leading to deadly fire scenarios (23% of fire deaths).[1]

3. Other principal ignition sources leading to deadly fire scenarios are operating equipment (40%) and small open flames (11%).[1]

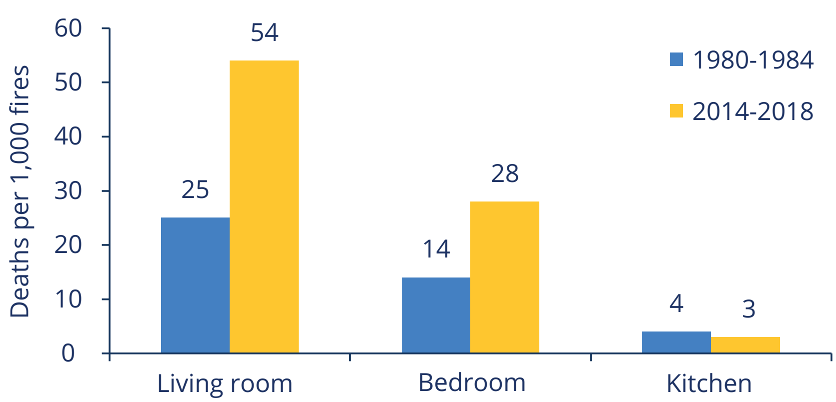
4. NFPA and other studies have shown that most fire deaths (about 95%) occur because of flaming fires and when fires spread beyond the upholstery furniture item, and even beyond the room of fire origin.[3,40,41] This implies that even in fires ignited by smoldering ignition sources, most fire deaths occur after transition from smoldering to flaming. More on fire statistics can be found at https://chemicalinsights.org//wp-content/uploads/2020/07/FireAnalysis_Brief.pdf.



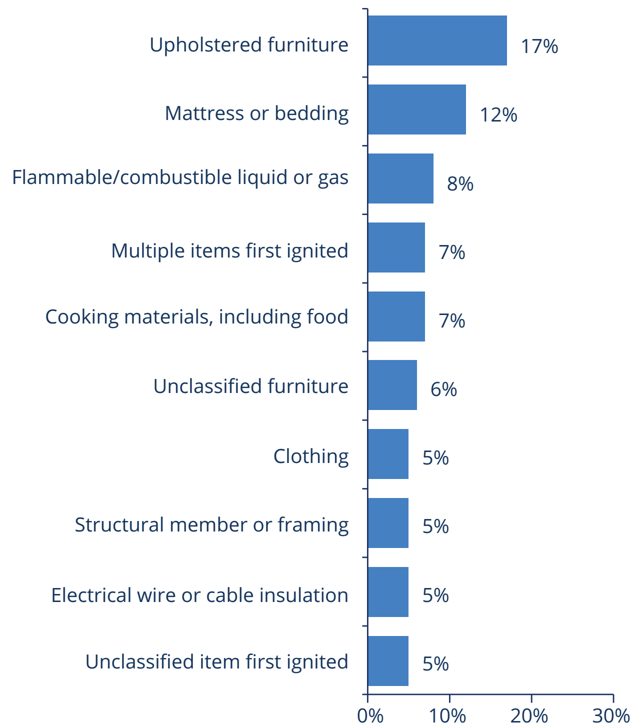
a) Deaths per 1,000 reported home fires by year and occupancy: 1980 – 2018.



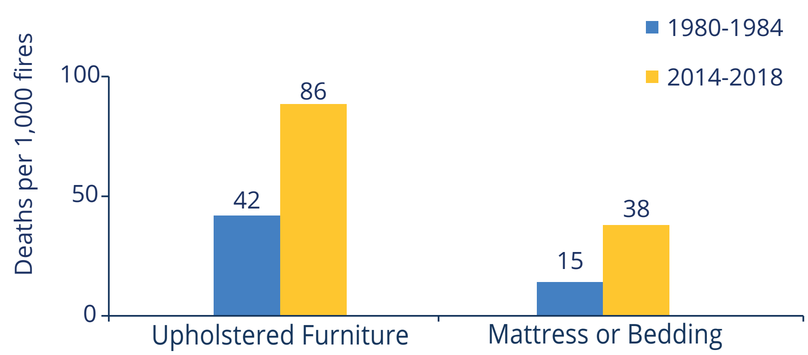
b) Leading areas of origin for deaths in home structure fires: 2014 – 2018.



c) Deaths per 1,000 fires in leading areas of origin: 1980 – 1984 vs. 2014 – 2018.



d) Leading items first ignited in home structure fires that resulted in death: 2014 – 2018.



e) Deaths per 1,000 fires that began with residential upholstered furniture or mattresses and bedding: 1980 – 1984 vs. 2014 – 2018.

Figure 3

Leading cases of home fires resulting in death by year, origin, and first item ignited.[1]

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2.2 Managing Fire Risks

Prevention is the key to mitigating fire risks. The following Table 1 details available tools for managing fire risks. According to the U.S. Fire Administration (USFA), smoke alarms should be tested and cleaned monthly, batteries, if required, changed when needed and replaced after 10 years.[43] NFPA and USFA recommends a working smoke alarm to be located on each level of the home, and inside and outside of every sleeping area.[14,43] Some smoke alarms comply with standards such as UL 217[44] and UL 268.[45] While some tools are more common to commercial buildings (such as sprinklers), their use are not limited and can expand to residential/single family homes.

Table 1
List of Tools Used To Reduce Fire Risk

Detectors and alarms	Smoke detectors and alarms	
	Carbon monoxide alarms	
	Heat detectors	
	Air sampling detectors	
	Notification appliances:	• Audible (bell, horn, etc.) • Visible (strobe lights) • Tactile (bed shaker)
Fire suppression tools	Sprinklers	
	Fire extinguisher	
	Fire blanket	
	Flame retardants	
Take preventative actions	Fire escape plan	
	Close your door[46]	

2.3 Flame Retardants

2.3.1 Key Federal and State Requirements and Guidelines

Regulations to prevent fire ignition of household products have been in place since the 1950s, and these regulations and recommendations have been continuously changing since then in the U.S. Flame retardants have been commonly used in product formulations to prevent or slow fire ignition. Table 2 summarizes key regulations and recommendations related to flammability and flame retardants. More on flame retardant regulations and guidelines can be found at https://chemicalinsights.org/wp-content/uploads/FireRegulations_Bulletin.pdf.

Table 2
Timeline of Key Events/Regulations on Flame Retardants Related to Residential Upholstered Furniture

1953	The U.S. Flammable Fabric Act was passed in 1953 to regulate the manufacturing of highly flammable clothing in response to a series of deaths in the 1940s from wearing rayon clothing.[47]
1967	Flammable Fabric Act was amended to include products/interior furnishings in addition to apparel and textiles.[48]
1970s	Polybrominated diphenyl ethers (PBDEs) were beginning to be added as flame retardants to consumer products.
1975	California introduced Technical Bulletin 117 (TB 117), requiring materials of upholstered furniture to pass open flame and cigarette smolder tests.
1984	California issued Technical Bulletin 133, requiring open flame flammability testing of completely assembled seating as used in public buildings.[49]
1993	ASTM E1537 issued as a regulatory test in the International Fire Code and in the NFPA Life Safety Code. ASTM E1537 is identical to CA TB 133 and NFPA 266.
1998 – 2001	NFPA 266, Standard Method of Test for Fire Characteristics of Upholstered Furniture Exposed to Flaming Ignition Source, was published in 1998; however, was withdrawn in 2001 because it was duplicative of ASTM E1537.
2000s	By then, extensive research showed that PBDEs were persistent, bioaccumulative, and toxic.
2004	The European Commission and U.S. EPA banned the use of Penta- and OctaBDE, two commercial mixtures primarily used in North America.[50]
2009	The US EPA issued a phase-out of DecaBDE production.[50]
2011	TDCPP was added to California Proposition 65 list.[51]
2013	California Technical Bulletin 117 was replaced with TB 117-2013 to a smolder only test.[11]
2017	CPSC accepted a petition to regulate flame retardants commonly used in furniture, children's products, electronic enclosures, and mattresses containing any member of the class of organohalogen flame retardants.[52]
2019	The California TB 133 was repealed.[53]
2019	The U.S. House of Representatives passed a bill to require that all furniture within the U.S. meet the California TB 117-2013 test, but this did not become law.
2020	At this time, 12 states and Washington D.C. have passed policies regulating flame retardants: ban on octaBDE and pentaBDE in 11 states, decaBDE in six states, and chlorinated Tris in five states and Washington D.C.
2020	California bans the sale of upholstered/reupholstered furniture, mattresses, and juvenile products that contain chemical flame retardant at levels above 1000 ppm, and has a labeling requirement implemented for products containing added flame retardants.[54]
2020	Congress passed the COVID-19 Regulatory Relief and Work from Home Act, requiring CPSC to promulgate TB 117-2013 as a national test standard.

2.3.2 Common Chemical Flame Retardants

Many different flame retardants are used in residential upholstered furniture and other furnishings, electronics, construction materials, and transportation products.[54] Flame retardants are added to meet regulations and fire performance requirements and decrease the ignitability of materials and/or inhibit the combustion process.[55] Flame retardants are often categorized based on chemical structure and include halogenated, nitrogen, and organophosphorus flame retardants (OPFRs). OPFRs are organic esters of phosphoric acid-containing alkyl chains or aryl groups, and they can be halogenated (often bromine or chlorine) or nonhalogenated. Other flame retardants are used such as ones based on aluminum, boron, or antimony.

Flexible polyurethane foam is commonly applied as cushioning material in residential upholstered furniture. Polyurethane foams are combustible with higher net calorific value compared to other RUF construction materials and may represent a significant fuel load in a home, therefore chemical flame retardants have been used to meet local fire performance standards.[56] Flame retardants, when detected in polyurethane foam in furniture, include[57]:

- Pentabromodiphenyl Ether (PentaBDE) – not produced since 2004, but still found in existing furniture
- Tris (1,3-dichloro-2-propyl) phosphate (TDCPP)
- Tris (1-chloro-2-propyl) phosphate (TCPP)
- A mixture of brominated and organophosphate flame retardants (2-ethylhexyl-2,3,4,5-tetrabromobenzoate (EH-TBB or TBB), bis(2-ethylhexyl)-2,3,4,5-tetrabromophthalate (BEH-TEBP or TBPH), triphenylphosphate (TPP), tris-isobutylated triphenyl phosphate (TBPP) and/or TPP analogs with various degrees of aryl isopropylation (iTPP))
- Phosphoric acid, P, P'-[2,2-bis (chloromethyl)-1,3-propanediyl] P, P, P', P'-tetrakis (2-chloroethyl) ester (V6)
- Tris-isobutylated triphenyl phosphate (TBPP)
- Isopropyl triphenyl phosphate (ITP) mix
- Methyl phenyl phosphate (MPP) mix

While these flame retardants are semi-volatile, designed to readily volatilize when in contact with a flame to extinguish it, this also means that they can migrate into surrounding air and dust in a typical indoor environment. Since 2005 and due to health concerns, PentaBDE has been phased out in a voluntary effort starting in 2004 (Table 2); however, the use of alternate flame retardants increased.[58] Today, the usage of organohalogen flame retardants is declining due to regulatory action and manufacturers' voluntary actions; however, the use of non-halogenated OPFRs is increasing.[59]

A variety of textiles are used as furniture materials, and they differ in construction (knitted, woven, and many types of nonwovens) and in the chemical nature of the fibers. Because of this, the flammability of textiles varies dramatically from very flammable cellulosic, e.g., cotton, and common synthetic fiber textiles to inherently flame resistant textiles. Different flame retardant chemicals and application methods have been optimized specifically for the different types of fabric: cotton, synthetic, and specifically for blend textiles that behave differently than cotton or synthetic alone. Flame retardants often used on or in fabric are compounds including ammonium, phosphate, melamine, borax, silicon antimony trioxide, and chlorine. Back-coating is the prominent method of application, commonly applied with halogenated flame retardant and vinyl-copolymeric or an acrylate-based mixture.[60] More on textile flammability treatment method is discussed in Section 2.4.

2.3.3 Health Concerns

Health concerns associated with residential upholstered furniture arise for both daily use and during a residential fire. Residential upholstered furniture, like other household products, can release volatile and semi-volatile organic compounds including flame retardants when added to furniture components, including the foam.[5] The release of these chemicals into the environment results in human exposure via inhalation, ingestion or dermal transfer. When residential upholstered furniture is ignited, there is the potential of fire spread but also the release of asphyxiant gases as well as elevated levels of polycyclic aromatic hydrocarbons and flame retardants in the air.[5,61] While all mentioned above are concerning, this document focuses on flame retardant technologies and their unintentional consumer health risks for exposure during typical use. This was considered in outlining key steps toward achieving residential upholstered furniture with lower risks in both fire and chemical exposure.

Health risk is characterized by dose and exposure assessments of a hazardous substance (Figure 4). Many chemical flame retardants have been identified as hazardous, and available dose and exposure studies have indicated human health risks associated with them.[51,59] This, in return, presents opportunities for risk management options in the design, construction and use of residential upholstered furniture.

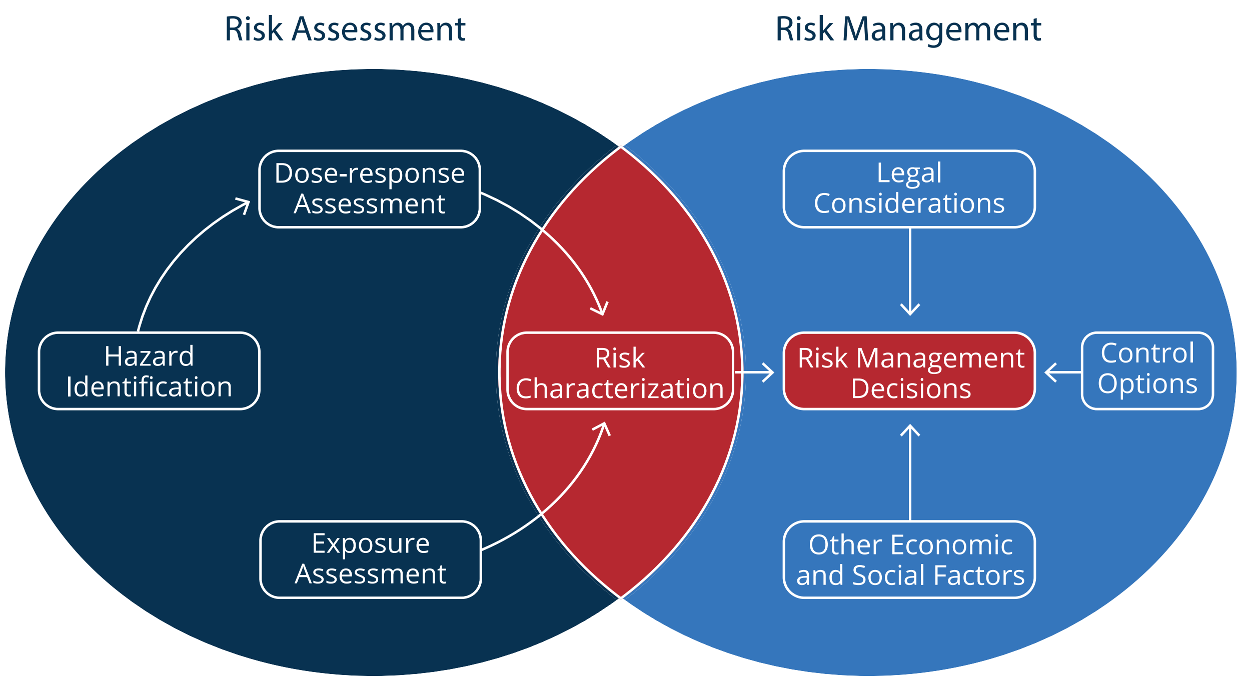

Figure 4

Diagram of NRC risk assessment/risk management paradigm, redrawn based on EPA Office of Research and Development, available from https://www.epa.gov/fera/nrc-risk-assessment-paradigm.[55]

2.3.4 Key Definitions to Identify and Quantify Health Risk

Hazard – A source of potential adverse health outcome. A hazardous material must have an exposure and a dose to cause an effect and thus risk.

Dose – The amount of a substance that passes through an epithelial layer and thus enters the body. Dose is often expressed as milligram (amount) per kilogram (a measure of body weight) per day (a measure of time) when people eat or drink contaminated water, food, or soil. In general, the greater the dose, the greater the likelihood of an effect.[62]

Exposure – Contact of a substance with boundary of the body – an epithelial layer. Exposure can come through three routes: inhalation, ingestion, or dermal contact.[62] Exposure may be short-term (acute exposure), of intermediate duration (semi-chronic exposure), or long-term (chronic exposure).

- Acute exposure: Exposure by the oral, dermal, or inhalation route for 24 hours or less.[63]
- Semi-chronic exposure: Repeated exposure by the oral, dermal, or inhalation route for more than 30 days, up to approximately 10% of the life span in humans (more than 30 days up to approximately 90 days in typically used laboratory animal species).[63]
- Chronic exposure: Repeated exposure by the oral, dermal, or inhalation route for more than approximately 10% of the life span in humans (more than approximately 90 days to two years in typically used laboratory animal species).[63]

Risk – The probability or chance of harmful effects to human or ecological health resulting from exposure and subsequent dose to a stressor, including any physical, chemical, or biological entity that can induce an adverse response.[62]

There is growing evidence that many flame retardants are hazardous as they have been shown to cause adverse developmental effects and cancer in animals after long-term exposure (Table 3).[47,48] Halogenated flame retardant compounds have structures that are similar to thyroid hormones, therefore, some of these compounds may act like thyroid hormones and interfere with the normal activity of those hormones.[17] Research suggests that the entire class of organohalogen flame retardants may have hazardous properties;[59] hazards associated with the 14 separate chemical classifications of organohalogen flame retardants are currently being investigated.[64] Studies have demonstrated that both halogenated and non-halogenated OPFRs are associated with adverse reproductive health and birth outcomes, asthma and allergic disease, early growth and adiposity, and may affect neurodevelopment, endocrine system, behavioral development, reproductive outcomes, preterm birth, respiratory outcomes, and allergic diseases, immune and nervous systems.[47,53] OPFRs have shown comparable toxicity activity to brominated flame retardants in the assays tested.[54]

Table 3
Selected Chemical Flame Retardants and Their Human Health Effect[65]

Chemical	Effect
Polybrominated Diphenyl Ethers (PBDEs), hydroxylated Polybrominated Diphenyl Ether (OH-BDEs)	Reproduction Thyroid Neurodevelopment
Tris (1,3 dichloro-2-propyl) phosphate (TDCPP)	Reproduction/Embryogenesis Thyroid Neurodevelopment
Triphenyl phosphate (TPP), TPP analogs with various degrees of aryl isopropylation (iTPPs)	Reproduction/Embryogenesis Thyroid
2-ethylhexyl-2,3,4,5-tetrabromobenzoate (TBB), bis(2-ethylhexyl)-2,3,4,5-tetrabromophthalate (TBPH)	Development Thyroid Reproduction

2.3.5 Environmental and Human Exposure

Flame retardants are ubiquitous in our products and environments, can migrate out of products, and be found in air and settled dust in the surrounding environment.[55,56] Flame retardant exposure to humans occurs via inhalation, hand-to-mouth contact, and dermal absorption.[50,67] Studies in humans and the environment have demonstrated that certain flame retardant chemicals can persist in the environment and bioaccumulate in people and wildlife.[48,56,68] Phase out of brominated flame retardants began in 2004 and has been effective in reducing the impact of certain flame retardants in typical settings. For example, measured exposures to pentabromodiphenyl ether (PentaPDE) has decreased since the phase out.[69] The use of TDCPP has decreased since 2014, coinciding with the addition of TDCPP to California Proposition 65 list.[69] Other flame retardants on Proposition 65 include Tris (2,3-dibromopropyl) phosphate and Tris (2-chloroethyl) Phosphate (TCEP) as all listed flame retardants have been found to be carcinogenic.[65,70-72] Use of OPFRs are rising, but OPFRs have higher vapor pressures compared to PBDEs, leading to increased off-gassing of OPFRs from treated products into indoor air.[73,74] OPFRs are often found at higher concentrations compared to PBDE peak exposure levels.[50] OPFRs, especially chlorinated OPFRs, are more soluble and can persist in water which fits the classification of persistent mobile organic compounds.[50] OPFRs have also accumulated in Arctic sediments at concentrations 10 − 100 times greater than those of PBDEs.[50]

Flame retardant dose levels in humans and wildlife have been measured, and OPFRs that have been used in residential upholstered furniture are shown to metabolize in the human body.[59,60] OPFRs have recently been detected in placental tissues, suggesting they may be transferred to the developing infant.[53]

Flame retardants are found in residential upholstered furniture manufactured with polyurethane foam. Duke University offers a screening program to U.S. consumers who would like to know if flame retardants are in their residential upholstered furniture and other children’s products. They may submit foam samples, voluntarily, to the Duke University Foam Project where they are analyzed, and results obtained. Recent data analysis obtained on more than 2,400 samples shows that flame retardants have been found in approximately 50% of the samples.[57,58] Studies have shown that added flame retardants migrate from upholstered furniture into surrounding air that we inhale, into our body through direct skin exposure, and through direct and indirect oral exposure to flame retardants on the furniture or in the settled dust near the furniture.[5,59] Our bodies metabolize these specific flame retardants added to residential upholstered furniture.[58] Specific flame retardants used in residential upholstered furniture have been identified as known health hazards. When exposed, our bodies metabolize these flame retardants, increasing human health risk.

The overall environmental impact of flame retardant usage in residential upholstered furniture should also be considered, and this brings a focus on the life-cycle of furniture. Life-cycle of a product encompasses raw material extraction, manufacturing, product use, and end of life including reclamation. The furniture industry, among many other industries, is transforming linear supply chains toward a closed loop, attempting to shift the economy from an extractive to a sustainable regenerative framework.[75] Furniture fabrication already has many elements in place. Notably, 1) pieces can be made to last generations; 2) an aftermarket exists of professional tradespeople who can extend longevity, i.e., upholsterers; and 3) secondary markets support furniture reuse through donation and resale. Moreover, re-upholstery components, like metals, foam, and cotton, can be diverted from the landfill into downstream recycling markets, and remnant fabrics can be sold or donated for reuse. Complications to this system occur when persistent chemicals are present in various materials. As a result, removing pollution is a pillar of a regenerative future, limiting recycling efforts to components without flame retardants so not to reintroduce to new products, like carpet padding.[75] This affects furniture reuse and other end of life options. Older pieces of furniture that have a TB 117 tag are likely to have foam with flame retardants, and these flame retardants migrate and mix with air and dust for consumer exposure and enter our soil and water resources.[76,77] Recommendations include: 1) utilize a labeling system on products prior to selling; 2) monitor air, soil, and water near waste/water treatment plants over time to monitor for persistent organic pollutants (POP); and 3) identify products for recycling and separate materials prior to disposal.[76,77]

2.4 Upholstered Furniture Fabrication Methods to Ensure Fire Safety

Common fabrication methods to reduce ignitability in the upholstered furniture market include[5,6]:

1. Chemical flame retardant added to the foam
2. Reactive flame retardant copolymerized/bound in the foam during manufacturing
3. Use of barrier material which delays/limits flame propagation to the underlying filling material
4. Cover fabric treated with flame retardant

Brominated, chlorinated, and OPFR flame retardants are all added flame retardants. In recent years, polymeric and reactive flame retardants have been proposed as more stable non-emissive alternatives to added flame retardants. Polymeric flame retardants are large molecules that do not migrate or volatilize in foam applications. Reactive flame retardants become part of the polyurethane compound during foaming and as such create a material with inherent fire resistance properties. These alternatives are more difficult to design as they can interfere with the foam production process (by changing reaction rates or curing times), and they are slower to volatilize after ignition so many applications have been found to be less efficient.[78]

Fire barriers are protective layers designed to prevent or delay ignition of the cushioning material (which is the main source of fuel and heat in upholstered furniture) and to reduce the fire growth rate and the fire size (heat release rate) after flaming ignition. A fire barrier is typically a fabric interliner placed between the cover fabric and the cushioning material. Fire barriers can accomplish a reduction in fire hazard by:

• limiting heat transfer (e.g., from a flame or an external heat source) to the padding material, thus limiting the rate at which combustible volatiles are generated; and by

• controlling the rate and location at which combustible volatiles and liquids (produced by melting or thermal degradation of the padding material) are released and able to burn.

These two mechanisms of action are physically-based (no chemical fire retardants needed) and can be referred to as heat and mass transfer effects, respectively. Fire barriers often rely on materials that have inherent improved fire performance (e.g., glass, carbon and polysilicic acid/rayon fibers).[79,80] Such materials with inherent improved fire performance combine heat and mass transfer mechanisms to other physical mechanisms of fire retardancy, like endothermic effects (associated to the endothermic decomposition of the material) and dilution effects (associated to the release of non-flammable gases during the decomposition of the material, e.g., water vapor, that decrease the concentration of combustible gases).[81]

There are several strategies implemented to make textiles flame retardant: inherently flame resistant fibers, chemical flame retardants, surface modifications, back-coatings, and emerging nanotechnologies such as layer-by-layer.[60] Cotton may be treated with either phosphorus or halogen flame retardants.[82] Older methods involved treating cotton with inorganic or water-soluble organic phosphates. Ammonium phosphate solutions can be applied to flame retard cotton; however, this is not commonly used today for upholstered furniture as the approach lacks suitable durability. Semi-durable cotton flame retardant treatments can be achieved by padding followed by temperature fixation of the chemistry to the fibers, which is suitable for furnishing applications. Back coating cotton textiles with low solubility ammonium polyphosphate is gaining momentum. There are more sophisticated finishing processes for cotton which can achieve almost permanent fixation of the flame retardant, but they are mostly applied to the protective apparels where they need to survive multiple industrial washings.[82,83]

Flame retardants may be added to synthetic fibers, e.g., polyester, at the different steps of production. Reactive phosphinate monomers can be incorporated in the polymer backbone during polymerization of polyester fibers. Highly thermal stable polymeric flame retardants can be incorporated into the polyester or polyamide fibers by melting the polymer and flame retardant together and spinning the fibers. Flame retardants may also be incorporated into polyester fibers using thermosol or exhaust processes. The thermosol process dips hot soft fibers into an organophosphate water-based solution. The organophosphate flame retardant is absorbed to the surface and after the water dries, the flame retardant remains.[82] In the exhaust process, emulsified flame retardant is used to take advantage of the flame retardant's high affinity to the polyester. This process is also used to dye fibers so dyes and flame retardants can be applied in the same processing step.

Modern upholstered furniture fabrics are more likely to be blends of synthetic and natural fibers. Unfortunately, blends are more flammable than cotton or synthetic textiles alone and the techniques and chemistries used to flame retard pure cotton or synthetic textiles do not work. Halogenated flame retardants are used to treat blends as they provide more robust response to ignition threats. Back coating the blend textile is the prominent way these flame retardants are applied. A very fine flame retardant particle dispersion, sometimes containing antimony trioxide, in an acrylic latex is applied to one side of the fabric. After curing, the latex and thus the flame retardant is attached to the fabric.[82,83]

3 Measuring Residential Upholstered Furniture Flammability and Exposure to Flame Retardant Chemicals

3.1 Human Exposure Routes

For humans, intake of flame retardants occurs via oral, inhalation, and dermal exposure routes. As described in Figure 5, oral exposure of flame retardant occurs when a person directly puts an object with a flame retardant in one's mouth, or indirectly from dust to hand then to mouth, for example.[63] The flame retardant is ingested and carried through the G.I. tract. Various organs are exposed once the flame retardant is metabolized, which then could lead to health impact. Some flame retardants are semi-volatile organics that can migrate from its source into the air and onto surrounding material surfaces, including building dust. These flame retardants can be released into the air as a volatile gas or particle forms and can be inhaled by mouth or nose. Inhaled air with flame retardant goes into one's lungs, then is metabolized in one's body. A fraction of direct contact to a surface with a flame retardant can be absorbed by one's skin and be metabolized, or direct hand contact with settled dust containing a flame retardant can be carried to the mouth for oral ingestion. The summation of all three exposure route makes up the total daily dose of a flame retardant.

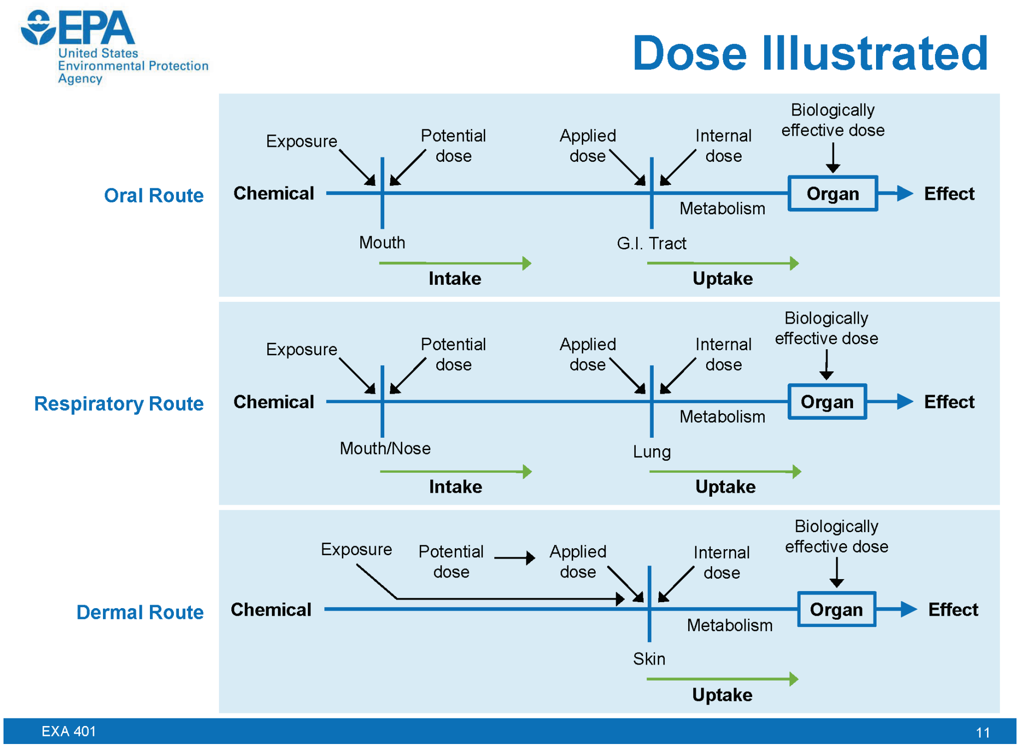

Figure 5

Dose concepts via oral, respiratory, and dermal route exposure, from U.S. EPA Risk Assessment Training and Experience Program, Module EXA 401, available from https://www.epa.gov/expobox/exposure-assessment-tutorials.[63]

3.2 Analytical Measurements of Chemical Flame Retardants in Residential Upholstered Furniture

Analytical methods for measuring commonly added flame retardants used in residential upholstered furniture and often found in air, soil, water, dust, products, human/wildlife serums, and tissues are available. Analytical instruments used include liquid chromatography-mass spectrometry and gas chromatography-mass spectrometry. Table 4 presents common analytical sampling and analysis methods based on source of exposure and environmental or biological matrix.

Table 4
Sample Collection, Extraction, and Analytical Methods of Detecting/Quantifying Flame Retardant

Source/ Fate of Transport	Exposure Route	Environmental Concentration Analysis		
		Sampling media/ preparation	Extraction	Analytical instrument
Air	Inhalation	Glass fiber filter and PUF plugs precleaned	Sonication, Acetonitrile	LC-ESI-MS/MS
Air	Inhalation	Glass fiber with Empore disk	Elution with Methanol	LC-ESI-MS
Dust	Dermal	Hand wipe with gauze	Soxhlet, sonicate with n-hexane and ethyl acetate	GC/MS[84]
Dust	Dermal, ingestion	Nylon dust collection thimble	Sonicate with DCM and hexane	GC/MS[84]
PUF	Dermal	n/a	Sonicate with DCM	GC/EI/MS[85]
PUF	Dermal	n/a	Sonicate with DCM	GC/ECNI-MS[85]
PUF	Dermal	n/a	Sonicate with DCM	HPLC-HRMS[3]
Blood serum	Dose	n/a	LLE	GC-LRMS
Adipose tissue	Dose	n/a	LLE	GC-HRMS
Human milk	Dose	Freeze dry	SLE	GC-HRMS
Human serum	Dose	Formic acid	SPE	LC-ESI-MS/MS
Tissues of humans, dolphins, sharks	Dose	Mix with Na_2SO_4	Soxhlet DCM, n-hexane	LC-ESI-MS/MS

APCI: Atmospheric pressure chemical ionization, DCM: dichloromethane, ECNI: electron capture negative chemical ionization, EI: electron ionization, ESI: electrospray ionization, GC/MS: gas chromatography–mass spectrometry, HPLC: high performance liquid chromatography, HRMS: high resolution mass spectrometry, ITD: ion trap detector, LC/MS: liquid chromatography mass spectrometry, LLE: liquid-liquid extraction, LRMS: low resolution mass spectrometry, PLE: pressurized liquid extraction, PUF: polyurethane foam, SLE: supported liquid extraction, SPE: solid phase extraction, TOF: time-of-flight, UPLC: ultra-performance liquid chromatography. Unless referenced, the rest are from Covaci et. al.[86]

3.3 Fire Testing for Residential Upholstered Furniture

The fire hazard associated with residential upholstered furniture can be reduced using two fundamental approaches:

- Fire Prevention (i.e., increase in ignition resistance)
- Fire Mitigation (i.e., reduction of the burning rate and/or heat release after ignition occurred)

Fire prevention aims to reduce the likelihood that a furniture item will become involved in a fire. It requires both smoldering and flaming ignition resistance tests because ignition in upholstered furniture can occur via smoldering sources (most often cigarettes) or via flaming sources (from small flames, like candles, to large flames spreading from other room items). The principal flaming ignition sources leading to deadly fire scenarios are large open flames from another burning item (25%) and small open flames (16%).[87] Furthermore, according to the National Fire Protection Association (NFPA),[40,88] the large majority of fire deaths (maybe up to 95%) occur in the presence of flaming when fire spreads beyond the upholstery furniture item. This implies that even in smoldering ignited fires, most fire deaths occur after transition from smoldering-to-flaming.

Fire mitigation aims to reduce the consequences of a fire and is based on tests that measure the reduction of a burning rate (most critically measured as heat release rate, which is the most important property in a fire[87]) and/or the total heat released after ignition has occurred, independent of the ignition mechanism. Although the use of fire barriers is a mitigative approach to decrease the probability of ignition of the filling material, they will not typically decrease the heat released if ignition of the padding occurs. This conceptual classification of fire testing in upholstered furniture is shown in Figure 6. Examples of applicable fire tests are shown in Table 5.

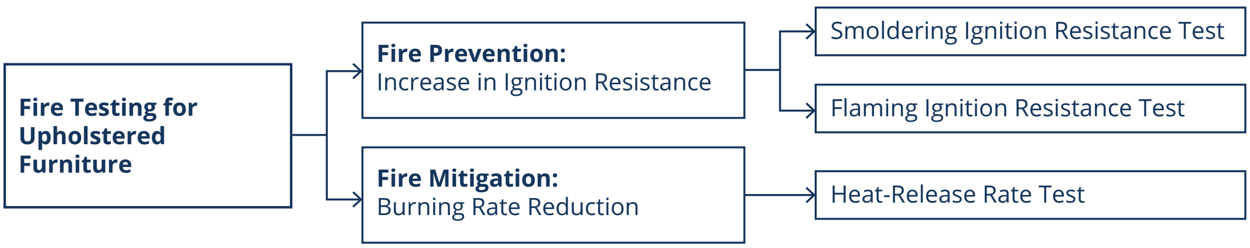

Figure 6

Fire testing classification in upholstered furniture.

Table 5
Fire Tests Currently Applicable to Upholstered Furniture

Smoldering Ignition Tests	NFPA 260, ASTM E1353, UFAC	Tests for individual components
	NFPA 261, ASTM E1352	Tests for composite systems
	CA TB 117-2013	Test for cover fabrics, barrier materials and resilient filling materials Will become a national testing standard in 2021
Open Flame Ignition Tests	BS 5852	Open flame test for individual furniture components
	ASTM E1537	Open flame test for assembled furniture
	ASTM E1474	Cone calorimeter application to upholstered furniture and mattress composites
Heat Release Tests	ASTM E1474	Cone calorimeter application in cored composites for PHRR and pool formation
	ASTM E1537	
	Cube test	

Based on the type (flaming or smoldering) and intensity of the ignition source, a variety of fire tests have been developed, but many are not standardized. A comprehensive overview of furniture fire safety regulations in Europe has been published recently.[89] As a result of the Congressional COVID-19 Regulatory Relief and Work from Home Act of December 2020, TB 117-2013 will be adopted as a national test standard for furniture in 2021, providing a testing requirement for cigarette smoldering. In the TB 117-2013 standard, fabric is tested using a standard foam and foam is tested using a standard fabric to minimize variability in test results.

3.3.1 Cigarette Smoldering Ignition Tests

In the U.S., standard tests specifically associated with residential upholstered furniture address only cigarette smoldering ignition. Such tests have been issued by NFPA (NFPA 260[90] and NFPA 261[48]), ASTM (ASTM E1352[91] and ASTM E1353[92]), and the State of California.[11,12] Furniture manufacturers (Upholstered Furniture Action Council) have also issued their own cigarette smoldering test (known as the UFAC test), with which many manufacturers comply. In practice, these tests are similar in that they assess char length and ignition from placing a cigarette on a fabric. NFPA 260, ASTM E1353, CA TB 117-2013, and the UFAC test assess the cover fabric by testing on a standard polyurethane foam. NFPA 260 and ASTM E1353 also allow the assessment of the smoldering performance of paddings. Note that paddings are typically foams but could be other materials. On the other hand, NFPA 261 and ASTM E1352 look at the composite system, with a specific assembly of fabric and padding. It is also of interest to note that the UFAC test is the only one that uses commercial cigarettes and that all commercial cigarettes in the U.S., are required to be reduced ignition propensity cigarettes – meaning that they are less likely to ignite fabrics than the cigarettes used in the other test methods, which are intended to simulate the cigarettes formerly sold in the U.S. with a much higher ignition propensity such as the NIST Standard Reference Material 1196A.

California has the only mandatory flammability standard for residential upholstered furniture in the U.S. It is the California Technical Bulletin 117-2013,[8] which is required for measuring the tendency of upholstery cover fabrics to smolder and contribute to fire propagation when subjected to a smoldering ignition source. If the cover fabric passes the test, the first layer (only) of padding materials must also pass the smoldering test, or a barrier (interliner) must be used with failing resilient materials. No open flame ignition test is contained within this standard, which replaced the long-used California Technical Bulletin 117, a standard that contained both smoldering and open flame tests.

The cigarette smoldering tests address testing of the individual components used in upholstered furniture. The smoldering tests typically divide materials into two classes, which could be Class A and Class B or Class I and Class II, where basically one of the classes indicates a pass and one indicates a failure. For a fabric to be acceptable for use in upholstered furniture, the material must be in the class with the better performance. Alternately, a barrier layer is to be added between the fabric and the padding to accomplish the desired smoldering ignition resistance of the full chair. A NIST study provided data to correlate the test results from smoldering tests to the ignition resistance of the upholstery furniture and the study showed evidence that these smoldering tests underestimate actual smoldering in actual furniture due to the test design.[5,6] Underwriters Laboratories research on upholstered furniture found that TB 117-2013 test results did not correlate with the ignition resistance of its study chairs.[5,6]

Nonetheless, there is room for improvement in the classification of materials using these smoldering ignition tests, and there is activity underway in the laboratories and in standards venues.

3.3.2 Open Flame Ignition Tests

The ignitability and fire performance of polyurethane foam have long been shown to be very poor, unless the foam was treated with fire retardant additives. Technologies exist to protect foam from exposure to fire, including open flame. Between 1975 and 2013, the state of California required that all polyurethane foam (which is the most common padding material used) in upholstered furniture comply with the small open flame standard in CA TB 117. The United Kingdom has required, since 1988, that polyurethane foam comply with a more severe small open flame standard, BS 5852,[93] and was joined by Ireland later.

Examples of studies demonstrating how the fire safety of residential upholstered furniture has been improved by using materials (fabrics and paddings) that have improved fire performance are available (supplement S). The work showed that foams that comply with a small open flame test provide a level of ignition protection that is significant (even if it is not enough on its own for full fire safety) and that the elimination of such a safeguard would result in an important lowering of fire safety. For example, one additional minute to escape would, in some cases, have meant the difference between being able, or not, to rescue a fire victim.

No active standard U.S. fire test exists to assess the resistance to flaming ignition sources for residential upholstered furniture. However, as discussed above, a fire test exists in the UK (BS 5852[2]). In BS 5852 an ignition source (which can be a gas flame or a wooden crib) is applied to an upholstered furniture composite. The most widely used ignition sources are crib 5, which the UK requires for polyurethane foam, and the ignition source one gas burner, which the UK requires for cover fabrics. There is no mandatory federal regulation in the U.S. to control the consequences of a flaming ignition.

There is also no standard fire test used in the U.S. to assess the transition from smoldering to flaming combustion, but research has been published that describes methodology that can assess that phenomenon.[94]

3.3.3 Heat Release Testing

Another fire test that is specifically addressing upholstered furniture is a generic small-scale test, the cone calorimeter (ASTM E1354[95]), which has an application test (ASTM E1474[96]) that indicates how upholstered furniture components and composites are to be tested. This test describes a specific set of instructions for specimen preparation and exposure heat flux. This has not been used for any official regulation but an extensive European Commission study (CBUF[97]) demonstrated that the results of the test were indicative of real scale fire performance of furniture, especially when dealing with the poorer fire performers. It is also especially important to note that the cone calorimeter test measures several of the key parameters essential for fire safety, namely ignitability, heat release and smoke release. Recently, NIST developed another bench-scale fire test (referred to as the "Cube test"),[18] based on the cone calorimeter, which can address upholstered furniture composites and components also but is primarily focused on its ability to rank the fire performance of fire barriers.[98]

3.3.4 Fire Mitigation via Barriers

Fire mitigation strategies can also be very effective as shown by a recent NIST study estimating the impact of 16 CFR Part 1633, the Federal Standard for mattress flammability.[99] The 16 CFR Part 1633 fire test[100] is a full-scale open flame test for the flammability of real mattresses and it is a regulatory tool for all mattresses sold in the U.S.; no upholstered furniture equivalent exists. Per bed fire, the adoption of the 16 CFR Part 1633 standard allowed approximately a 70% reduction in fire deaths due to flaming ignition with about 50% to 80% of the mattresses replaced so far.[101] Although 16 CFR Part 1633 is a heat release test, compliance has often been met by using fire barriers.

Fire barriers have proven to be an effective solution to protect upholstered furniture[5,6] as they can prevent the ignition of the padding material and fully suppress flaming with small candle-like ignition sources. This was confirmed with Underwriters Laboratories research on residential upholstered chairs where chairs with a barrier material (and no flame retardants) were found to have significantly lower peak heat release rates and lower fire hazards (temperature, smoke and carbon monoxide) than chairs with and without flame retardants.[5,6] However, when confronted with large flames that may compromise the barrier (typically because the pyrolysis products penetrate through the barrier and ignite the padding), a more comprehensive goal is to slow down the burning rate to provide enough time for the occupants to escape and for first responders to intervene before flashover.

Fire barriers can accomplish such a reduction in fire hazard by:

- Limiting heat transfer (e.g., from a flame or an external heat source) to the padding material, thus limiting the rate at which combustible volatiles are generated.
- Controlling the rate and location at which combustible volatiles and liquids (produced by melting or thermal degradation of the padding material) are released and able to burn.

These two mechanisms of action are physically-based (no chemical fire retardants needed) and can be referred to as heat and mass transfer effects, respectively.

Fire barriers often rely on materials that have inherent improved fire performance (e.g., glass, carbon and polysilicic acid/rayon fibers).[24,102] Such materials with inherent improved fire performance combine heat and mass transfer mechanisms to other physical mechanisms of fire retardancy, like:

- Endothermic effects (associated to the endothermic decomposition of the material)
- Dilution effects (associated to the release of non-flammable gases during the decomposition of the material, e.g., water vapor, that decrease the concentration of combustible gases).[103]

Fire barriers can also exploit chemical mechanisms of action by including chemical fire retardants. Figure 7 shows the possible mechanism of actions in a fire barrier.

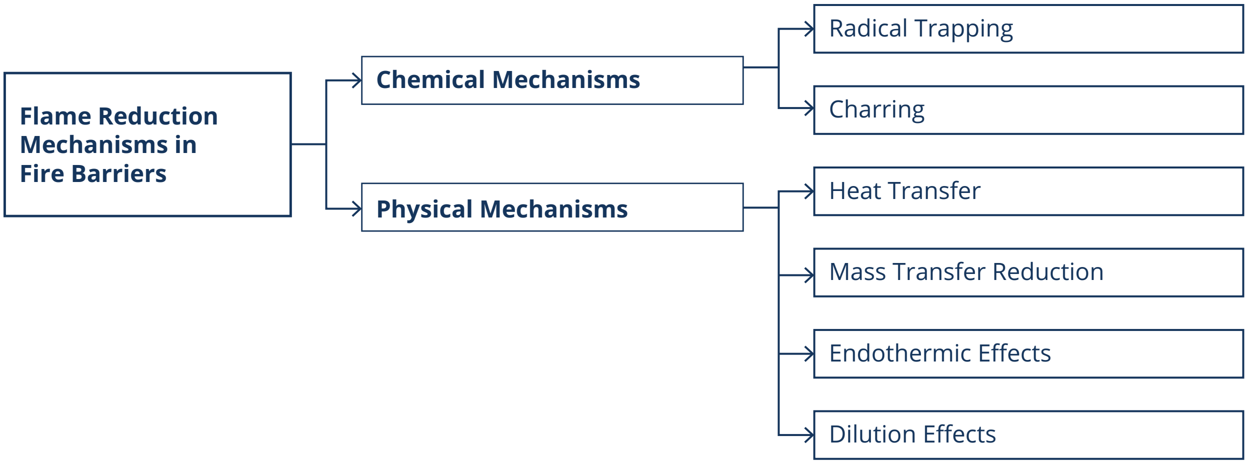

Figure 7

Flame reduction mechanisms in fire barriers.

Based on their mechanisms of action, fire barriers can be classified as passive fire barriers (which act by physical mechanisms and do not contain fire retardants), and active fire barriers (which act by a combination of chemical and physical mechanisms and generally contain fire retardants). This classification is summarized in Figure 8.

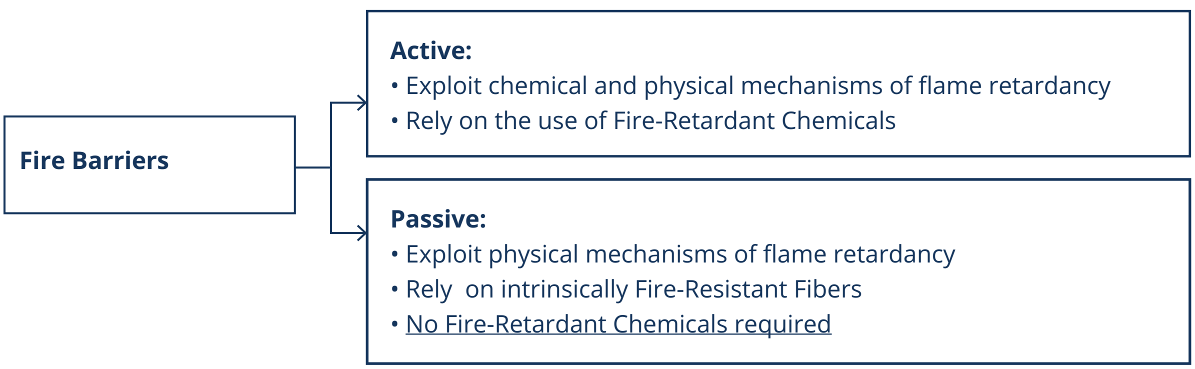

Figure 8

Active vs. passive fire barrier classification.

• Barrier material has the potential to reduce open flame fire hazards. The use of a barrier with no flame retardants added for residential upholstered furniture has been shown to have a significant impact on the burn parameters of the upholstered chairs.[5,6,25,60,98] Chairs with an effective fire barrier should have lower heat release rate, consequently resulting in lower fire hazards including room temperature during ignition, smoke density, and carbon monoxide and hydrogen cyanide concentrations when compared to upholstered chairs with no flame retardants.[5,6,13]

• One kind of barrier material is the woven fiberglass with coating. This material does not contribute any additional volatile organic compounds to be released.

3.3.5 Fire Performance

It is typical that any fire test will target a specific fire scenario and is likely not to be effective for most other fire scenarios. For example, a material designed to resist ignition by a small open flame may be overwhelmed and ignite when exposed to a larger flame or to a flame of the same intensity, but for a longer duration. Also, the fact that a fabric complies with a smoldering ignition resistance test does not imply that it will comply with a flaming ignition test or vice versa. In fact, there is usually a trade-off between resistance to smoldering or to flaming ignition and research has shown that fabrics treated for resistance to smoldering ignition often are more prone to open flame ignition.[104] For example, charring polymers (typically cellulosic materials such as cotton or rayon) are more susceptible to smoldering ignition and growth than non-charring thermoplastic polymers, such as polyesters, polyolefins, or acrylics, which are unlikely to be ignited by cigarettes but are prone to melting and dripping (including generating flaming drips) and are often easily ignitable by open flame sources.

The fire scenario in a fire test should be chosen based on the fire hazard (which is the propensity for generating harm) and fire risk, which is the product of the likelihood of experiencing a fire and the severity of the consequences of the fire. The consequences of fires include fire deaths, fire injuries, loss of homes, loss of businesses, or simply the occurrence of a fire.

Ultimately, transition from smoldering-to-flaming and ignition because of open flames originating in other fires are the two leading scenarios which cause home fire deaths. Strategies to address such scenarios by fire prevention seem unlikely due to the intensity and the duration of the ignition source, and fire mitigation appears a more robust approach (less susceptible to fire scenario) to decrease furniture fire hazard.

Some U.S. states have adopted or are discussing the introduction of regulations that would ban the use of many chemical flame retardants in residential upholstered furniture to reduce the propensity of the furniture to undergo flaming ignition or fire growth after ignition. In this regard, passive fire barriers offer a potential solution. Fire barriers have proven to be an effective solution to protect upholstered furniture[5,6] as they can prevent the ignition of the padding material and fully suppress flaming with small candle-like ignition sources. However, when confronted with larger flames that may compromise the barrier, a more realistic goal is to slow down the burning rate to provide enough time for the occupants to escape and for first responders to intervene before flashover.

S Supplemental Information

S.1 Studies Comparing Residential Upholstered Furniture With Improved Fire Performance to Furniture That Has Not Met A Flaming Ignition Test

A study at Southwest Research Institute (SwRI), as part of a National Institute of Justice (NIJ) program,[2] looked at the effectiveness of these standards in terms of improving the fire safety of polyurethane foam and especially that of upholstered furniture containing such foam. The study involved full scale fire tests on existing furniture and on upholstered furniture mockups constructed with one of four foams and one of two fabrics, and small-scale tests on the foam and fabric combinations. One of the foams used complied with BS 5852 crib 5, one complied with CA TB 117-2000,[105] and the others were standard non-fire retarded foams of different densities. Foam compliant to CA TB 117-2000 normally contained added flame retardants. One fabric complied with the NFPA 701[106] fabric flammability test and one did not. In that study it was found that upholstered furniture mock-ups with CA TB 117-2000 foam provided significantly longer times to ignition or delays before a fire became significant. For example, with an ignition source at the back the delay was approximately seven minutes. Moreover, the peak heat release rate was significantly lower for the CA TB 117-2000 foam. When CA TB 117-2000 foam was combined with an NFPA 701 fabric, the upholstered furniture mock-ups resisted ignition even with a significant flaming source on the seat. For comparison purposes, mock-ups with foam complying with BS 5852 crib 5 were able to resist ignition in virtually all cases, even with fabrics that are not fire retarded.

Earlier work on a full-scale study of identical residential U.S. sofas differing purely in the nature of the foam showed that the sofa with CA TB 117-2000 foam required the use of a more severe ignition source than the one with non-fire retarded foam. Moreover, even with the more severe ignition source, the sofa with CA TB 117 foam gave occupants an extra minute to escape. However, once the sofa ignited, sofas eventually caused a self-propagating fire and reached flashover conditions. In the same study, a residential UK sofa, with foam complying with BS 5852 crib 5, did not ignite at all. This result is representative of similar types of results obtained in various proprietary full-scale studies comparing the three types of foams.

S.2.1 Current Common Applied Flame Retardants Used in Furniture Fabrication[102,107-110]

Material	Flame Retardant and other Additives
Cotton (non-durable)	Mono or diammonium phosphates (or combine both)
Cotton (non-durable)	Short chain water soluble ammonium polyphosphate
Cotton (non-durable)	Ammonium sulfamate or sulfate
Cotton (non-durable)	Monoguanidine dihydrogen phosphate or diguanidine monohydrogen phosphate
Cellulosics (non-durable)	Borax (Sodium borate)
Polyester (non-durable)	Guanidine phosphate and amidosulfonic acid
Cotton (semi durable)	Phosphoric acid and urea or dicyandiamide followed by heating
Cotton and cotton-based blends (durable)	Long chain ammonium polyphosphate and its coated versions
General use (durable)	Decabromodiphenyl ether-antimony oxide backcoating
General use (durable)	Antimony trioxide mix
General use (durable)	Brominated polymers
Cotton and cotton-based blends (durable)	Tetrakis(hydroxymethyl)phosphonium salts and urea followed by ammonia cross-linking and oxidation
Cotton and cellulosic-rich substrates (durable)	N-methylol phosphonopropionamide derivatives
Polyester fiber comonomer (durable)	Dioxaphosphorinane (DOPO) adduct with succinic acid
Polyester fiber comonomer (durable)	Adduct of benzenephosphinic acid and acrylic acid
Polyester fiber exhaust (durable)	Cyclic liquid diphosphonate and triphosphonate mixture
Polyester fiber spinning (durable)	Poly (bisphenol A methylphosphonate)
Rayon fibers	1,3,2-dioxaphosphorian-2,2-oxy-bis-(5,5-dimethyl-2-sulphide)
Cotton	UV-Curable Flame Retardant Coating. Examples: tri(acryloyloxyethyl) phosphate

S.2.2 Common Currently Applied Flame Retardants Used in Resilient Filling Materials[16,56,58,70,85,110-116]

Material	Flame Retardant and other Additives
Polyurethane Foam	Poly (bisphenol A methylphosphonate)
	Tris (2-chloro-1-methylethyl)phosphate (TCPP) and melamine
	Tris (1,3-dichloro-2-propyl)phosphate (TDCP)
	P,P′[2,2-bis(chloromethyl)-1,3-propanediyl] P,P,P’,P’-tetrakis(2-chloroethyl)ester phosphoric acid
	Ammonium polyphosphate
	Expandable graphite (graphite intercalated with sulfuric acid)
	Tricresyl phosphate (TCP)
	Tris (p-t-butylphenyl) phosphate
	Oligomeric ethyl ethylene phosphate
	Oligomeric ethyl ethylene phosphate polyol
	Oligomeric phosphonate polyol
	Phosphoric acid, methylphenyl diphenyl ester
	Phosphoric acid, bis(methylphenyl) phenyl ester

S.2.3 Common Flame Retardants Used in Coatings and Finishes[110]

Category	Material	Flame Retardant and other Additives
Coatings	Polyurethane foam and textiles	Layer-by-layer (LbL) coatings: carbon nanotube, carbon nanofiber, polyhedral oligomeric silsesquioxanes (POSS), silica and α-zirconium phosphate
	Polyurethane foam	LbL coating: polyethyleneimine (PEI) and polyacrylic acid (PAA) & sodium montmorillonite clay
Non-intumescent Coatings	Polyester fabric	Inorganic nanoparticles: LbL assembly of alumina coated silica with silica nanoparticles
	Cotton Fabric	OctaAmmonium polyhedral oligomeric silsesquioxane (POSS) ((+) POSS) coupled with OctaTMA POSS ((−)POSS) or aminopropyl silsesquioxane oligomer (AP)
		Aluminum oxide nanoparticle-based coating
	Polycarbonate Films	Branched polyethylene imine (BPEI), negative
		Silica nanoparticles (average diameter: 30 nm) & positive alumina coated
		Silica nanoparticles (average diameter: 10 nm) and a UV-curable acrylic aliphatic polyurethane resin
	Polyurethane Foam	Anionic vermiculite and cationic boehmite
		Carbon nanofibers coupled with polyacrylic acid
		Nanoparticle coating of Polyacrylic acid (PAA)-stabilized aluminum hydroxide (ATH) and polyethylene imine (PEI)

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