ATTACHMENTS TO

GBH INTERNATIONAL

COMMENTS

MAY 2008

ATTACHMENT 1

F288–07/08

3603.2, Chapter 45 (New)

Proponent: Cynthia A. Wilk, Department of Community Affairs-Division of Codes and Standards, State of NJ

1. Revise as follows:

3603.2 Quantities exceeding the maximum allowable quantity per control area. The storage and use of flammable solids exceeding the maximum allowable quantity per control area as indicated in Section 2703.1 shall be in accordance with Chapter 27 and this chapter.

> **Exception:** Buildings storing mattresses containing polyurethane foam that have been tested and meet the criteria of 16 CFR Part 1633 are not required to comply with this chapter and Chapter 27.

2. Add standard to Chapter 45 as follows:

CPSC

16 CFR Part 1633-06 Standard for the Flammability of Mattress Sets

Reason: (IFC) Using the definitions set forth in the International Fire Code Section 3602.1 polyurethane foam has been identified to be a flammable solid. Tests have documented that polyurethane foam meets both the "burns so vigorously and persistently when ignited…" and the "self sustained flame rate of greater than 0.1 inch (2.5mm) per second…" benchmarks[i]. This creates a large impact applying the fire code to storage and mercantile facilities that contain both upholstered furniture and mattresses. The proper application of the code with this new information would require compliance with this chapter due to the presence of flammable solids. While this may not be widely known or understood by enforcers or the regulated community, it is nevertheless substantiated by current code language and laboratory analysis.

The proposed exception will provide a remedy for all Group S and M occupancies that store, display, and sell mattresses. The CPSC Standard 16 CFR Part 1633 tests the mattress assembly as it is produced which more accurately represents the hazard as a whole. As per section 1633.3(b) of the CPSC Standard, the mattress set is deemed to comply when the test specimen meets both of the following criteria: (1) The peak rate of heat release does not exceed 200 Kilowatts at any time within the 30 minute test and (2) The total heat release does not exceed 15 megajoules for the first ten minutes of the test. Without this exception, facilities that store, display or sell mattresses, like those facilities that store, display or sell upholstered furniture containing polyurethane foam, would be required to comply with Chapter 36 and Chapter 27.

[i] 16 CFR1500.44 Testing For National Association of State Fire Marshals on Poly Foam/ Vtec #100-2519-2/Tested: November 2, 2006. VTEC Laboratories Inc.

Cost Impact: The code change proposal will reduce the cost of construction.

Analysis: A review of the standard proposed for inclusion in the code, CPSC 16 CFR Part 1633-06, for compliance with ICC criteria for referenced standards given in Section 3.6 of Council Policy #CP 28 will be posted on the ICC website on or before January 15, 2008.

Public Hearing:	Committee:	AS	AM	D
	Assembly:	ASF	AMF	DF

ATTACHMENT 2

FIRE AND MATERIALS
Fire Mater. 2005; **29**:15–26
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Do open flame ignition resistance treatments for cellulosic and cellulosic blend fabrics also reduce cigarette ignitions?

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SUMMARY

Mattresses/bedding and upholstered furniture are subject to ignition by cigarettes (smoulder) and open flames leading to injuries, fatalities and property damage. There are mandatory and voluntary cigarette ignition standards in the USA for mattresses (16 CFR 1632) and upholstered furniture (UFAC voluntary standards) as well as open flame ignition standards in California (TB 117) and the UK (BS 5852). Open flame ignition standards are being considered/developed for these products. Some suggest that fire retardant (FR) treatments to prevent/reduce open flame ignitions also reduce cigarette ignitions. Some reports suggest that the smoulder ignition propensity of some cellulosic fabrics can be affected adversely by open flame ignition resistance treatments. Ignitions caused by cigarettes and open flames result from different types of combustion that are retarded by different mechanisms. Flaming combustion is a gas phase reaction and occurs when heat causes degradation of the polymer releasing volatile products that undergo rapid oxidation in the air, whereas smouldering combustion is a direct oxidation of either the polymer or its char. The results of textile/fibre industry studies with FR treated upholstery fabrics and a critical review of the available published literature indicate that cigarette ignition propensity of cellulose fabrics is complicated and affected by many factors and that smoulder ignition resistance of these fabrics can be affected adversely by open flame ignition resistance treatments. Copyright © 2004 John Wiley & Sons, Ltd.

1. INTRODUCTION

Mattresses/bedding and upholstered furniture ('soft furnishings') can be ignited by cigarettes and open flames (e.g. matches, cigarette lighters, candles) leading to injuries, fatalities and property damage. The US Consumer Product Safety Commission (CPSC) and some US states are considering/developing open flame ignition standards for these products [1–4]. There are already mandatory and voluntary cigarette ignition standards in the USA for mattresses [5,6] and upholstered furniture (UFAC voluntary standards; [7]) as well as open flame ignition

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standards for furniture in California [8–12] and the UK [13]. It is suggested by CPSC that fire retardant (FR) treatments to prevent/reduce open flame ignitions also reduce cigarette ignitions [2]. However, many reports suggest that the smoulder ignition propensity of some 100% cellulosic and predominately cellulosic fabrics can be affected by some open flame ignition resistance treatments.

Cotton is greater than 50% of the fibre used in the US upholstery and slip cover market (871 600/1 513 500 217.7 kg (480 lb) bales] [14,15]. It is estimated that cotton and cotton blend fabrics are more than 40% of the present US upholstered furniture fabric market [45]. Cotton is also over 40% of the fibre used in the mattress/filled bedding market in the US (484 000/1 164 000 bales) [14–16]. This paper considers the effect of open flame ignition treatments for cellulosic and cellulosic blend fabrics on smoulder ignition propensity. The results of an industry study are presented and the available published literature is reviewed.

1.1. Combustion

Once ignited, virtually all common textile fabrics will burn. Textile fabrics burn by two distinctly different processes. Since the fibres that make up the fabrics are composed of large, non-volatile polymers, *flaming combustion* (e.g. that caused by an open flame source, such as a match) requires that the polymer undergo decomposition to form the small, volatile organic compounds that constitute the fuel for the flame. The combustion of polymers is a very complex, rapidly changing system that is not yet fully understood [17,18]. For many common polymers, this decomposition is primarily pyrolytic with little or no thermo-oxidative character. *Smouldering* or *glowing combustion* (e.g. that caused by a cigarette) on the other hand involves direct oxidation of the polymer and/or chars and other non-volatile decomposition products. The general smouldering behavior of cotton fabric was approximately described by Krasny [19] and Ohlemiller [20]. Gases and chars can be produced by two different paths (oxidation and pyrolysis [in the absence of air]) and may differ in their chemical nature. Unfortunately, smouldering is also subject to acceleration by common alkali metal ions such as sodium, potassium or calcium [21–25], which occur in varying levels in USA and foreign cottons [26]. These metal ions catalyse the oxidation reaction, producing more rapid heat release and promoting smouldering. Cotton in both the raw state and as dyed and finished fabric frequently contains metal ions in sufficient quantity to cause smouldering when exposed to a cigarette or similar ignition source. The source of the fibre, level of preparation and treatment water (water hardness) can all be important to the level of alkali metal ions. Laundering, or even water soaking, of cotton fabrics often reduces the metal ion content to such a level that the fabrics are not ignited by cigarettes. Soiling of cotton or rayon fabrics can affect smouldering potential [27,28].

Because the relevant chemistry is very different for flaming and smouldering combustion, approaches to prevent the two combustion modes for fabrics/textiles are usually different.

1.2. Flame retardant treatments

Flame retardant chemical treatments are needed if most fabrics are to resist either flaming or smouldering combustion. Fire retardants for textiles have been known since the mid-1600s when theater curtains were treated with clay and plaster of paris to decrease fire hazards. By 1740, alum was being used and ammonium phosphate was introduced for cotton fabrics in the later

1700s. Since then, the science and technology of textile flame retardation has developed to allow a variety of different approaches to fit different end uses and ignition exposure conditions.

Flame retardant chemicals, which are used to make textiles *flame resistant* (i.e. meet established governmental conformance standards or specifications [29]), may affect ease of ignition, combustion or both. In the case of textile fabrics of 100% thermoplastics, such as nylon, polyester and olefin, flame retardants are generally not needed to prevent ignition by small flames (e.g. in the vertical flame test required by the US children's sleepwear standard [30]; bottom edge ignition for 3 s). These fabrics melt and withdraw from flames and other heat sources, which usually prevents their ignition. This is the reason that untreated polyester garments are often used to comply with the US Consumer Product Safety Commission children's sleepwear federal standard [30]. However, if thermoplastic fabrics are used as upholstery fabrics the withdrawal from the flame could allow the filling material to ignite even though the fabric might not ignite. Also, thermoplastic fabrics after melting can ignite. Thus, thermoplastics would have to be treated with chemical additives or backcoated for some end uses (e.g. upholstery fabrics).

Cellulosics, such as cotton and rayon, as well as other non-thermoplastics that are char formers, are not inherently ignition resistant and usually must be chemically treated to prevent ignition by small flames [31,32]. Blends of non-thermoplastics and thermoplastics, such as cotton/polyester fabrics, are also prone to ignition, since the non-thermoplastic component prevents the withdrawal of the fabric from the heat source [32]. These types of blends are difficult to make flame resistant.

1.2.1. FR control of flaming combustion of fabrics. There are five general approaches to reducing the vulnerability of fabrics/textiles to ignition and flaming combustion: (1) Coatings may be applied to shield fabrics from heat sources and prevent volatilization of flammable materials. These may take the form of simple protective coatings or, more commonly, the treatment of fabrics with inorganic salts that melt and form a glassy coating when exposed to ignition sources. In more advanced forms, intumescent coatings are used which produce non-flammable gases and a char that has sufficient plasticity to expand under the pressure of the gases to yield a thick, insulating layer [33,34]. (2) Thermally unstable chemicals, usually inorganic carbonates or hydrates, are incorporated in the material, often as a backcoating so as to preserve the surface characteristics of the carpet or fabric. Upon exposure to an ignition source, these chemicals release CO_2 and/or H_2O, which dilute and cool the flame to the point that it is extinguished. (3) Materials that are capable of dissipating significant amounts of heat are layered with the fabric or otherwise incorporated in a composite structure. These may be as simple as metal foils or other heat conductors or as complicated as a variety of phase-change materials that absorb large quantities of heat as they decompose or volatilize. If sufficient heat is removed from the point of exposure, the conditions for ignition are not reached. (4) Chemicals capable of releasing free radical trapping agents, frequently organobromine or organochlorine compounds, may be incorporated into the fabric. These release species such as HBr and HCl which can intervene in the oxidation reaction of the flame and break the chain reaction necessary for continued flame propagation. (5) Chemicals capable of modifying the pyrolysis of the polymer making up the fibre may divert the pyrolysis to reduce the emission of the volatile degradation products that constitute the fuel for the flame. This approach is most useful with cellulosic fabrics. In a slightly different approach, chemical species can be incorporated in fabrics made from thermoplastic fibres to catalyse the degradation of the fibre polymer to reduce the melt viscosity of the polymer and cause more rapid flow away from the ignition source.

Condensed-phase-active retardants that work on cellulosics such as cotton or rayon will have little or no effect when applied to other fibres, such as polyester and nylon. On the other hand, gas-phase-active retardants, which act primarily as flame poisons to prevent flaming combustion, are effective on virtually all fibre types since the flame chemistry is similar for a wide variety of fuel gases. Such retardants do not need to be in close contact with the polymer and can be located in a separate phase, such as a backcoating, as long as they are close enough to the heat source to be volatilized at the same time as the gaseous polymer decomposition products. Some of the most effective flame poisons are chlorine and/or bromine compounds. The aromatic halogen compounds, such as the brominated biphenyl ethers/oxides (e.g. decabromodiphenyl ether/oxide, 'DBDPE'), are usually preferred, as they are more resistant to light and thermal processing. Other organobromine compounds, such as hexabromocyclododecane ('HBCD') are also used. These compounds are not effective flame poisons until they are converted into species such as HBr, and particularly $SbBr_3$ or complex oxybromides when in the presence of an antimony III oxide synergist [35]. What are needed are good sources of the halogen free radicals that act as free radical traps and, thus, effective fire retardants.

Backcoatings of DBDPE or HBCD with Sb_2O_3, which can be effective on virtually all fibre types, are the main treatments being used in the UK to meet the open-flame ignition requirements of BS 5852. An acrylic resin is needed to make them semi- to fully durable.

1.2.2. FR control of smouldering combustion. Inhibition of smouldering combustion generally takes one of two forms [21,36,37]: (1) Physical barriers similar to those used for flaming combustion may be effective. These barriers may be simple heat shields that prevent the polymer from reaching ignition temperatures or they may function as gas barriers to prevent oxygen from reaching the solid fuels. Barriers are usually either intumescent materials [33,34] or compounds such as borates that form glasses on heating. (2) Chemical approaches are usually based on inhibition of the polymer oxidation reaction. The general theory of such action is similar to that of gas phase inhibition but the radical trapping agents must be significantly less volatile or they escape the oxidation zone too rapidly. For effective smouldering suppression, the chemical intervention is usually directed at the oxidation of CO to CO_2 which is the most highly exothermic step in the oxidation sequence.

2. CIGARETTE SMOULDERING IGNITION

The results of open flame ignition tests and smoulder ignitions tests are test method dependent. The open flame tests for furniture all have different pass/fail criteria [2,3,9,10,13], which helps explain why a fabric will pass one test and fail another. Whether the cigarette is on a horizontal surface (e.g. mattress test) or in the crevice/vertical surface (e.g. furniture test) can affect the results of smoulder ignition tests [38]. The smouldering behavior of cigarettes on substrates is different from that of cigarettes burning in air [19]. The type of cigarette and the burning rate of the cigarette can also have an effect [39,40]. Light density fabrics (e.g. sailcloth) can have high ignitions with fast smouldering cigarettes, while heavy density fabrics (e.g. cotton duck) can have high ignitions with slow smouldering cigarettes [40,41]. Gann *et al.* [42,43] showed that cigarettes can be modified (some combination of reduced tobacco packing density, less porous paper, smaller cigarette circumference and no citrate [burn additive] in the paper) to have a lower relative ignition propensity than conventional cigarettes. This has led to 'fire safe' cigarette legislation in New York state (passed in 2000), which requires less fire-prone cigarettes that have a lower propensity to ignite soft furnishings (regulations issued Dec 2003, effective 28 June 2004) [44]. The US Congress is also considering fire safe cigarette legislation. If lower ignition propensity cigarettes become mandatory, there could be a weakening of the ignition strength of the standard commercial cigarette used to determine cigarette ignition resistance. A substitute ignition source is being sought. Whether the upholstery fabric is soiled or used also can affect smouldering potential and is most likely dependent on the type of soiling. Wanna and co-workers reported that used or soiled fabrics became more resistant to smouldering ignition compared with the unsoiled fabrics [27,28].

Published literature indicate that the flammability of cellulosic fabrics is very complicated and that the smoulder ignition propensity of some cellulosic fabrics can be affected by open flame ignition resistance treatments.

Dwyer *et al.* [22] and Hirschler [45] investigated the smouldering cigarette ignition propensity of upholstery fabrics typically available in the consumer marketplace. Of the 500 fabrics tested, only 145 fabrics were ignitable by cigarettes, all of them predominantly (or completely) cellulosic. Hirschler [45] found a fabric density threshold [200–250 g m^{-2} (5.9–7.4 oz/yd^2)] above which the percentage of cellulosic fabrics that are ignitable, and flame spread rate of fabrics in a flaming ignition test are all unaffected. Others have found that lighter weight cotton fabrics [$< 407\,g\,m^{-2}$ ($<$ 12 oz/yd^2)] are usually less ignition prone (Class I fabrics) than heavier weight cotton fabric in the UFAC fabric classification (smoulder) test [46,47]. Dwyer *et al.* [22] report that the upholstery fabrics' contents of sodium and potassium salts, their concentrations of cellulosics, and their basis weights correlate with ignitability.

The California Bureau of Home Furnishings (CA BHF) in reports/publications in the 1970s [46,47] found that:

Treatments to reduce flammability are usually ineffective as smoulder inhibitors, and sometimes only compound and intensify smouldering problems; cellulosic fabrics are the most hazardous in terms of smouldering potential and the hazard increases as the fabric weight increases; thermoplastic fabric systems perform well in cigarette tests; cellulosic/thermoplastic blends >36% by weight of thermoplastic fibres pass the smouldering combustion tests and as the % thermoplastic approaches 35% the tendency to smouldering is greatly diminished; barrier systems are a valid approach to smouldering inhibition of furniture systems; effects of fabric weaves and constructions upon smouldering were uncertain; fabric weight, nature of the primary substrate and fabric fibre content appear to be the most critical to fabric/substrate system smouldering in cigarette tests.

Additional flammability studies of 700 articles of upholstered furniture by the CA BHF [48,49] found: cellulosic content of the upholstery fabric to be the most important factor in cigarette ignition resistance; resistance was greater when cellulosic content was 0–29%, less when cellulosic content was 30%–79% lowest when cellulosic content was 80%–100%; thermoplastic fibre in upholstery fabric appears to convey cigarette ignition resistance until the cellulosic content exceeds about 80%; cellulosic fabrics of $\geqslant$12 oz/yd^2 were less cigarette ignition resistant than fabrics $<$12 oz/yd^2; cigarette ignition resistance is likely to be related to style and shape of article, type and weight of fabric, amount of resin backcoating, and nature of the underlying substrate and is most likely to occur in the crevice area of upholstered furniture which is 100% cellulosic fibre, with no resin backing, and a blended untreated cotton batting substrate directly beneath the fabric.

Krasny [19] in his review for the National Bureau of Standards (now National Institute of Standards and Technology) as part of the Cigarette Safety Act of 1984 (P.L. 98-567) found 'that some materials which have good cigarette ignition resistance do not necessarily have good small flame ignition resistance and *vice versa*'; 'that cigarettes induce smouldering in medium to heavy weight cellulosic fabrics, with consequent heat transfer to the padding, but in contact with a small flame cellulosic fabrics char and until the char breaks, protect the padding'; and that thermoplastic fabrics tend to resist cigarette ignition but shrink, curl and melt upon contact with open flame and can expose the padding.

The US Department of Agriculture, Agricultural Research Service (USDA, ARS) studied smoulder resistance extensively in the late 1960s, 1970s and early 1980s and developed many treatments for cotton and cotton blend fabrics [21,36,37]. They found that cellulosic fabrics are very susceptible to cigarette-induced smouldering combustion, their smouldering characteristics are complex, metal salts increase the smouldering of cotton fabrics, and adding synthetic fibre to cotton lowers the smoulder rate.

In summary, cellulosic fabrics can smoulder, whereas, thermoplastic fabrics and cellulosic/thermoplastic blend fabrics (>30%–35% thermoplastic fibre) do not smoulder. For cellulosic fabrics, some have found lighter weight fabrics less smoulder ignition prone, some have found heavier weight fabrics less smoulder ignition prone, and others have found no correlation with fabric weight, type of treatment or percentage of treatment add-on and smoulder ignition propensity. The behavior of cellulosic and cellulosic/thermoplastic blend fabrics in cigarette/smouldering ignition tests is affected by many factors (e.g. fabric weight, air permeability, blend composition in blend fabrics, substrate tested over, etc.).

2.1. UK standard (BS 5852)

In the UK testing (using BS 5852 test methods [13]) for the British Furniture and Furnishings Regulation[‡] is done over combustion modified high resilient (CMHR) foam, and so, it is generally the case that all flame resistant FR textiles that pass over non-FR foam would pass both tests. Also in the UK if a fabric is 75% or greater cellulosic it does not have to pass the open flame test if a barrier is used. In the UK cellulosic fabrics, if they are FR treated, can be backcoated with DBDPE and antimony oxide or pad-dry-cure treated with Proban® or Pyrovatex®. Pyrovatex® and Proban® treated fabric also are used as barrier/interliner/fire-blocker to meet BS 5852. Some data indicate that Proban® and Pyrovatex® work well to resist open flame combustion but sometimes poorly and unpredictably to prevent cigarette ignitions (H. Talley, UFAC, personal communication, 2002).

2.2. Upholstered Furniture Action Council (UFAC) studies

Tests by UFAC have shown that cigarette ignition propensity of 100% cotton fabrics does not correlate with the weight of the fabric [50]. In studies with fabrics backcoated in the USA and the UK to pass BS 5852 and the 1997 CPSC test [52], most cotton fabrics that were UFAC Class I became Class II. (If the vertical char of any of the three test specimens is $\geqslant 44$ mm

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[‡] The British Furniture and Furnishings Regulation became law in the UK in 1988. It is based on the 1988 version of British Standard 5852 (BS 5852), which has a 20 s ignition time.

(1.75 in) or if there is an obvious ignition of the PUF substrate, this is a Class II fabric and is considered a failure of the test. UFAC Class II fabrics require an approved barrier between the fabric and conventional polyurethane foam in the horizontal seating surfaces; Class I fabrics can be used directly over conventional polyurethane foam [7].) The authors concluded that the fire performance of cellulosics is very complex and depends on many things, such as, method of yarn preparation (e.g. open-end vs ring spun), yarn type, fabric construction, and dyeing and finishing methods. The aesthetic of the 100% cotton fabrics were also altered by the FR-backcoating. They concluded that pad-dry-cure (topical or immersion) fabric treatment and backcoating were not the answer to the remainder of the cigarette ignition problem of 100% cotton fabrics. More specifically:

Pad-dry-cure/precondensate-ammonia cured 100% cotton fabrics: 12 fabrics (open-end and ring spun yarn fabrics; fabric weight range from 7.1 to 21 oz/yd^2) were immersion treated (8 Class I, 4 Class II before treatment); 2 of 6 Class I changed to Class II; 1 of 4 Class II was unchanged (3 of 4 changed to Class I).

FR backcoated 100% cotton fabrics: 11 fabrics were backcoated in the USA to pass BS 5852 (7 Class I, 4 Class II before treatment); 1 of 7 Class I changed to Class II; 3 of 4 Class II stayed Class II. 9 of the 11 fabrics were backcoated in the UK to pass BS 5852 (5 Class I, 4 Class II); 5 of 5 Class I changed to Class II; 4 of 4 Class II stayed Class II.

2.3. Study by the US textile/fibre industry

In 1998, the American Textile Manufacturers Institute/American Fiber Manufacturers Association (ATMI/AFMA) had 31 upholstery fabrics (Ref. [52], Table E), selected to represent the variety of fibre types, blends, weights, and constructions typical in the US marketplace, FR-backcoated at a commercial backcoating operation in the UK to pass BS 5852 [52]. Each fabric was treated with a FR latex backcoating (DBDPE and Sb_2O_3 and acrylic latex) to comply with the British Furniture and Furnishings Regulation [13]. Two of the 31 ATMI/AFMA fabrics (Ref. [52], fabrics N and P) could not be treated to meet the British test criteria. The other 29 fabrics were found to meet the requirements of the British regulation by a NAMAS[§] certified laboratory. All were returned to the USA for further testing.

Reimann [52] tested the 31 fabrics for open flame ignition using the 1997 CPSC draft standard [51]. Reimann discusses the differences in the CPSC 1997 test for the seating area and the dust cover [51], and BS 5852 for the seating area [13], which are similar (small butane flame (35 mm), 20 s). Some of the differences are: the butane gas delivery system for the CPSC test is more complex; the BS 5852 test is over CMHR foam and the CPSC test is over non-FR foam; the fabric soaking procedure (BS 5852 30 min in specified hardness water; CPSC 24 h soak in tap water); and the pass/fail criteria (in BS 5852 smouldering is allowed if it extinguishes in <15 min, flaming cannot extend to the sample sides or seat front although a flame can extend up past the top of the seat back if it recedes and self extinguishes in <120 s; in CPSC test, failure occurs when any smouldering occurs >120 s or when the sample burns or smoulders to any edge, top, sides or seat front). (The CPSC 2001 test [2] differs from the CPSC 1997 test [51]. The main differences are that the pass/fail criteria for post-ignition smouldering/glowing combustion

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[§] National Accreditation of Measurement and Sampling, a service of the United Kingdom Accreditation Service (UKAS). UKAS specifies criteria that laboratories must meet. Only a laboratory that has been accredited by UKAS can issue a NAMAS report or certificate.

time is extended from 120 s to 15 min and a seating barrier test, using BS 5852 Crib #5 as the ignition source, is added as an alternative to the seating area test. BS 5852 test method [13] now uses a 15 s ignition time and the EU is considering adopting the current BS 5852 as a CEN standard. Also, there is movement in the UK to change the British FFR officially to 15 s.)

In 1999, 30 of the 31 fabrics (no fabric P was available) were tested for smoulder ignition resistance before and again after FR-backcoating at the Grundy Textile Evaluation Laboratory, Philadelphia University, using the UFAC fabric classification test [7]. In *open-flame* testing, 14 of the fabrics failed the CPSC 1997 test (Ref. [44], Table J). Five of the seven 100% cotton fabrics and two of the six other predominately cellulosic (⩾70%) blend fabrics failed the test (Table I). Some of the fabrics (e.g. G, Y and BB) that failed the 1997 CPSC test [51] would likely pass the 2001 CPSC test [2] because of the change in the P/F criteria for smouldering (120 s vs 15 min).

The *smoulder* ignition testing results obtained by the Grundy Textile Evaluation Laboratory, Philadelphia University for ATMI/AFMA were as follows for back-coated versus non-back-coated fabrics:

- 1 fabric *improved* in cigarette ignition resistance (UFAC Class II became UFAC Class I)
- 5 fabrics became *less resistant* to cigarette ignition (UFAC Class I became UFAC Class II)
- 24 fabrics *did not change* their UFAC Classification (all remained UFAC Class I).

A Class II fabric is considered a failure in the UFAC fabric classification test.

As discussed earlier as the percentage of thermoplastic fibre in a cellulosic blend fabric approaches 30%–35%, the tendency of a fabric to smoulder is greatly diminished [46,47]. Because of this the test data for the 13 fabrics in the study that are predominately cellulosic (⩾70% cotton, rayon, or linen) and for the two fabrics that are 66% cellulosic were evaluated separately. These data show (see Table I; smoulder data from industry study; open flame data from Reimann [52]:

- 1 fabric *improved* in resistance to cigarette ignition;
- 5 fabrics *got worse* (failed the UFAC test) in resistance to cigarette ignition;
- 6 fabrics *were unchanged* in resistance to cigarette ignition;
- The two fabrics that are 66% cellulosic (fabrics D, R) were unchanged in cigarette ignition resistance and passed the open-flame test; and
- Whether a predominately cellulosic fabric changed from Class I to Class II or remained Class I was not correlated with fabric weight or percentage add-on of the backcoating.

2.4. CPSC 2001 briefing package

Khanna [53] concludes from CPSC testing that the CPSC 2001 draft standard [2] contains provisions to limit both flaming and smouldering combustion; that although the standard does not utilize a smouldering ignition source, the provisions account for smouldering combustion. This may be true for some upholstered furniture fabrics but CPSC's own testing indicates that 'Cellulosic flame resistant treated upholstery fabrics may not always resist both small open flame and cigarette ignition' [54]. In tests of 40 fabrics, conducted by CPSC, three FR backcoated fabrics ignited when exposed to a cigarette [55]. All the fabrics that ignited were cellulosic (cotton) fabrics. More specifically:

Table I. Summary of UFAC fabric classification (smoulder) test results for FR-treated fabrics.

Code	Fibre content	Fabric wt oz/yd^2 (g/m^2)	Add-on % oz (g)	UFAC fabric classification test results before and after FR-backcoating* (open flame test results† [failure mode‡])
I	92% cotton, 8% rayon	20.2(684.8)	11 2.24(64)	Class II to Class I (passed BS 5852; passed CPSC 1997)
T	100% cotton	7.5(254.3)	21 1.58(45)	Class I to Class II (passed BS 5852; failed CPSC 1997 [F])
Z	59% linen, 41% cotton	7.6(257.6)	10 0.74(21)	Class I to Class II (passed BS 5852; failed CPSC 1997 [F])
Y	100% cotton	10.7(362.7)	16 1.72(49)	Class I to Class II (passed BS 5852; failed CPSC 1997 [S])
BB	100% cotton	6.9(233.9)	25 1.75(50)	Class I to Class II (passed BS 5852; failed CPSC 1997 [F/S])
CC	100% cotton	6.6(223.7)	17 1.12(32)	Class I to Class II (passed BS 5852; failed CPSC 1997 [F])
A	60% cotton, 12% rayon, 28% nylon	22.7(769.5)	9 2.14(61)	Stayed Class I (passed BS 5852; failed CPSC 1997 [F])
C	96% rayon, 4% PET	18.7(633.9)	5 0.91(26)	Stayed Class I (passed BS 5852; passed CPSC 1997)
E	100% cotton	6.7(227.1)	15 0.98(28)	Stayed Class I (passed BS 5852; passed CPSC 1997)
F	62% rayon, 38% cotton	13.9(471.2)	7 0.95(27)	Stayed Class I (passed BS 5852; passed CPSC 1997)
G	100% cotton	12.8(433.9)	22 2.77 (79)	Stayed Class I (passed BS 5852; failed CPSC 1997 [S])
H	100% cotton	10.0(339.1)	17 1.68 (48)	Stayed Class I (passed BS 5852; passed CPSC 1997)
Q	69% cotton, 31% rayon	11.3(383.2)	13 1.47 (42)	Stayed Class I (passed BS 5852; passed CPSC 1997)
D	66% cotton, 16% nylon, 2% PET, 16% wool	16.4(556.1)	12 2.03 (58)	Stayed Class I (passed BS 5852; passed CPSC 1997)
R	10% cotton, 56% rayon, 34% PET	9.7(328.9)	27 2.63 (75)	Stayed Class I (passed BS 5852; passed CPSC 1997)

*Industry data determined by Philadelphia U. for ATMI/AFMA using Ref. [7].

†Ref. [52].

‡Failure mode: F, flame; S, smoulder.

UK chair study [54]: 27 chairs with complying FR-fabrics (14 predominately cellulosic) were tested using a mockup over non-FR-foam. Three of 14 cellulosic fabrics failed the cigarette ignition test.

Additional fabrics [55]: 40 fabrics (21 FR; 19 non-FR) were tested in the UFAC and CPSC mock-up test. 34 of 40 resisted cigarette ignition; 6 cotton fabrics, including 3 FR-backcoated fabrics, ignited.

3. CONCLUSION

Inhibition of smouldering combustion and flaming combustion require very different types of chemical retardant action. Smoulder retardants can be either physical barriers or oxidation inhibitors. Flaming combustion retardants cause inhibition by alteration of either the decomposition or oxidation reactions.

Backcoatings utilize gas-phase-active retardants, which act as flame poisons to prevent flaming combustion and can be effective on virtually all fibre types. However, backcoatings need to be considered as systems, not individual compounds, since the halogenated compounds (e.g. DBDPO) are not effective unless they are combined with antimony oxide to make them an effective flame poison and an acrylic resin to make them semi- to fully durable. It has been shown that some backcoating and pad-dry-cure (topical) treatments, which most likely would be used to prevent open flame ignition of upholstered fabrics, can negatively affect smoulder resistance of cellulosic fabrics.

The behavior of 100% cellulosic and cellulosic/thermoplastic blend upholstery fabrics (more than 40% of the fabrics and over 50% of the fibre in the present US upholstered furniture market) in flammability tests is complicated. It appears to be affected by many factors including fabric weight, fabric construction, yarn preparation (open-end vs ring spun), alkali metal content and dyeing and finishing methods as well as possibly other variables. Developers of effective mandatory or voluntary standards for open flame ignition of upholstered furniture or mattress/bedding need to consider the effect of open flame ignition resistance treatments on smoulder ignition resistance of 100% cellulosic and predominately cellulosic fabrics.

REFERENCES

1. US Consumer Product Safety Commission (CPSC). *Standard to Address Open-Flame Ignition of Mattresses/Bedding.* Advanced Notice of Proposed Rulemaking. 66 Federal Register 51886; Oct. 11, 2001.
2. US Consumer Product Safety Commission (CPSC). *CPSC Briefing Package on Upholstered Furniture Flammability: Regulatory Options.* Oct. 30, 2001. (Test Method, pp. 11–15 & Tab C, 151–180).
3. California (2002). (Draft 2/2002) *Proposed Update of Upholstered Furniture Flammability Standard.* Technical Bulletin 117 Requirements, Test Procedures and Apparatus for Testing the Flame and Smolder Resistance of Upholstered Furniture. California Bureau of Home Furnishings and Thermal Insulation (http://www.bhfti.ca.gov/techbulletin/tbl17_draft_2002.pdf).
4. California (2003). (Proposed TB 603). *Requirements and Test Procedure for Resistance of a Residential Mattress/Box Springs Set to a Large Open-Flame* (http://www.bhfti.ca.gov/ab603.htm).
5. 16 CFR 1632. Standard for the Flammability of Mattresses and Mattress Pads. 16 *Code of Federal Regulations* (Subchapter D—Flammable Fabrics Act Regulations) part 1632.
6. California TB 106. *Test Procedure and Apparatus for Testing the Resistance of a Mattress or Mattress Pad to Combustion Which a Smoldering Cigarette* (techbulletin/106.pdftechbulletin/106.pdfTechnical Bulletin 106).
7. Upholstered Furniture Action Council (1990). *UFAC Test Methods* (http://info@ufac.org/testmethods.htm).
8. California TB 116. *Requirements, Test Procedure and Apparatus for Testing the Flame Retardance of Upholstered Furniture* (techbulletin/116.pdftechbulletin/116.pdfTechnical Bulletin 116).

9. California TB 117: US State of California, Dept. of Consumer Affairs, Bureau of Home Furnishings and Thermal Insulation. Technical Bulletin 117. *Requirement, Test Procedures and Apparatus for Testing the Flame and Smoulder Resistance of Upholstered Furniture* (techbulletin/117.pdf techbulletin/117.pdfTechnical Bulletin 117).
10. California TB 133. *Flammability Test Procedure for Seating Furniture for Use in Public Occupancies* (techbulletin/tb133.pdftechbulletin/tb133.pdfTechnical Bulletin 133).
11. California TB 121. *Flammability Test Procedure for Mattresses for Use in High Risk Occupancies* (techbulletin/121.pdftechbulletin/121.pdfTechnical Bulletin 121).
12. California TB 129. *Flammability Test Procedure for Mattresses for Use in Public Buildings* (techbulletin/tb129.pdftechbulletin/tb129.pdfTechnical Bulletin 129).
13. British Standard BS-5852: 1990. The 1988 British Furniture and Furnishings Regulation, *Assessment of the Ignitability of Upholstered Seating by Smouldering and Flaming Ignition Sources*, Dec. 1990.
14. *Cotton Counts Its Customers*. 2000 edn. National Cotton Council: Memphis, TN, 2000.
15. Rearick WA, Wallace ML, Martin VB, Wakelyn PJ. Flammability considerations for raised surface apparel. *AATCC Review* 2002; **2**:12–15.
16. *National Purchase Diary* (retail sales), 2000 annual data.
17. Howell BA. Design of solid state phase active organohalogen flame retardants. In *Proceedings of 13th Annual BCC Conference on Recent Developments in Flame Retardancy of Polymeric Materials, June 2002, Stamford, CN*, Lewin M (ed.). Business Communications Co., Inc.: Norwalk, CN, 83–92.
18. Salamone JC. *Polymeric Materials Encyclopedia*, 4th edn. CRC Press: Boca Raton, FL, vol. 4, 1996, 2422–2426.
19. Krasny JF. *Cigarette Ignition of Soft Furnishings—A Literature Review with Commentary*. Report No. 2, NBSIR 87-3509, US National Bureau of Standards, Oct. 1987.
20. Ohlemiller TJ. *Modeling of Smoldering Combustion Propagation*. NBSIR 84-2895 [US] National Bureau of Standards, 1984.
21. Donaldson DJ, Yeadon DA, Harper Jr RJ. Smoldering phenomenon associated with cotton. *Textile Research Journal* 1983; **53**:160–164.
22. Dwyer RW, Fournier LG, Lewis LS, *et al.* The effects of upholstery fabric properties on fabric ignitabilities by smoldering cigarettes. *Journal of Fire Sciences* 1994; **12**:268–283.
23. Ihrig AM, Smith SL. The role of alkali and alkaline earth metal ions in cellulosic smoldering. *Journal of Fire Sciences* 1994; **12**:357–374.
24. Krasny JF. A simple method for reducing cigarette fires. *Textile Chemist and Colorist* 1992; **24**:12.
25. McCarter RJ. Smoldering combustion of cotton and rayon. *Journal of Consumer Product Flammability* 1977; **4**: 346–358.
26. Brushwood DE. Metals in domestic and non-domestic cottons and their frictional properties. *AATCC Review* 2002; **1**:20–24.
27. Wanna JT, Polo A, Schettino D. The smoldering potential of used upholstery fabrics: unsoiled vs soiled. *Journal of Fire Sciences* 1996; **14**:144–158.
28. Wanna JT, Rouse CA, Chen PL, Henderson GE, Greear LC. Smolder potential and characterization of used upholstery fabrics. *Journal of Fire Sciences* 1996; **14**:379–392.
29. ASTM D 4391. Standard Terminology Relating to the Burning Behavior of Textiles. Section 7, Textiles. *Annual Book of ASTM Standards*. Vol. 07.02. ASTM: West Conshohocken, PA, 2000; 408–410.
30. 16 CFR 1615. Standard for the Flammability of Children's Sleepwear: Sizes 0 through 6X. 16 *Code of Federal Regulations* (Subchapter D—Flammable Fabrics Act Regulations) part 1615.
31. Wakelyn PJ, Rearick W, Turner J. Cotton and flammability—overview of new developments. *American Dyestuff Reporter* 1998; **87**:13–21.
32. Horrocks AR. Flame retardant finishing of textiles. *Reviews in Progress in Colouration* 1986; **16**:62–101.
33. 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**:143–154.
34. Dombrowski R. Intumescent barrier coatings. *AATCC Review* 2003; **3**:13–16.
35. Kaspersma JH. FR mechanism aspects of bromine and phosporous compounds. In *Proceedings of 13th Annual BCC Conference on Recent Developments in Flame Retardancy of Polymeric Materials, June 2002, Stamford, CN*, Lewin M (ed.). Business Communications Co.: Norwalk, CN, 2002; 83–92.
36. Donaldson DJ, St. Mard HH, Harper Jr RJ. Imparting smolder-resistance to cotton upholstery fabrics. *Textile Research Journal* 1979; **49**:185–190.
37. Donaldson DJ, Yeadon DA, Harper Jr RJ. Smoldering characteristics of cotton upholstery fabrics. *Textile Research Journal* 1981; **51**:196–202.
38. Wanna JT, Chen PL. Results of a preliminary study of ignitions in flat vs crevice configuration. *Journal of Fire Sciences* 1998; **16**:15–24.
39. Damant GH. The cigarette as an ignition source. In *Fourth International Conference on Fire Safety, San Francisco, CA, Jan. 1979*. Product Safety Corp.: Mountain View, CA.
40. Wanna JT, Zelius P. Effect of cigarette variables on ignition propensity of various fabrics. *Journal of Fire Sciences* 2001; **19**:341–353.

41. Wanna JT, Tewarson A. Ignition propensity of fabrics. *Journal of Fire Sciences* 2001; **19**:401–411.
42. Gann RG, Harris Jr RH, Krasny JF, Levine RS, Miller RS, Ohlemiller TJ. *The Effect of Cigarette Characteristics on the Ignition of Soft Furnishings.* Report No. 3, Technical Study Group Cigarette Safety Act of 1984, and NBS Technical Note 1241, US National Bureau of Standards, Oct. 1987.
43. Gann RG, Stecker KD, Ruitberg S, Guthrie WF, Levenson MS. *Relative Ignition Propensity of Test Market Cigarettes.* NIST Technical Note 1436, National Institute of Standards and Technology: Gaithersburg, MD, 2001.
44. Fire Safety Standard for Cigarettes. Chapter 284 of laws of 2000, Section 15-c (2)(a) Executive Law of the State of New York. (The Standard Uses: ASTM E 2187-02b. *Standard Test Method for Measuring the Ignition Strength of Cigarette.* ASTM: West Conshohocken, PA, 2002.)
45. Hirschler MM. Comparison of the propensity of cigarettes to ignite upholstered furniture fabrics. *Fire and Materials* 1997; **21**:123–141.
46. Damant GH, Young MA. Smoldering characteristics of fabrics used as upholstered furniture coverings. *Journal of Consumer Product Flammability* 1977; **4**:60–113.
47. Damant GH, Young MA. Flammability classification of fabrics used as upholstered furniture coverings. *Journal of Consumer Product Flammability* 1977; **4**:329–345.
48. McCormack JA, Damant GH, Williams SS. Cigarette evaluation of 450 pieces of residential upholstered furniture. *Journal of Fire Sciences* 1986; **4**:135–147.
49. McCormack JA, Damant GH. Flammability studies of 700 articles of upholstered furniture. In *International Conference on Fire Safety*, Jan. 12, 1988, Hilado CJ (ed.), Produce Safety Corp., San Francisco, USA, 1998, vol. 13, 145–158.
50. Ziolkowski J, Talley H. The effects of FR backcoatings on the cigarette ignition propensity of 100% cotton fabrics. In *AFMA Flammability Conference, Mar. 9*, American Furniture Manufacturers Association Greensboro, NC, USA, 1999.
51. US Consumer Product Safety Commission (CPSC). *CPSC Regulatory Options Briefing Package on Upholstered Furniture Flammability*, Oct. 28, 1997. (draft Test Method, 394–412).
52. Reimann KA. Evaluation of CPSC upholstered furniture flammability test. In *Proceedings of 2000 Beltwide Cotton Conferences.* National Cotton Council: Memphis, TN, 2000; 827–837.
53. Khanna R. Cigarette-open flame relationship. *CPSC Memorandum to Dale Ray.* Oct. 23, 2001. [Ref. 2 (US CPSC, 2001), 232].
54. Fansler L. *CPSC Technical Report: Summary of Flammability Tests Upholstered Furniture Project (1998–2000).* 19 Oct. 2000. [Ref. 2 (US CPSC 2001), 263–283].
55. Stafford G, Bernatz A. UFAC vs CPSC cigarette tests of upholstery fabrics. *CPSC Memorandum to Dale Ray.* 30 May 2000. [Ref. 2 (US CPSC 2001), 514–522].

ATTACHMENTS 3-4

29. Bertelo, C. A., W. F. Carroll, M. M. Hirschler and G. F. Smith. *Proc. 11th Int. Conf. Fire Safety*, C. J. Hilado, ed., San Francisco: Product Safety, p. 192 (1986).

30. Bertelo, C. A., W. F. Carroll, M. M. Hirschler and G. F. Smith. *Fire Safety Science, Proc. 1st. Int. Symp.*, C. E. Grant and P. J. Pagni, eds., Washington:Hemisphere, p. 1079 (1986).

31. Beitel, J. J., C. A. Bertelo, W. F. Carroll, A. F. Grand, M. M. Hirschler and G. F. Smith. *J. Fire Sci.*, 5:105 (1987).

32. Galloway, F. M. and M. M. Hirschler. In *Mathematical Modeling of Fires*, ASTM STP 983, J. R. Mehaffey, ed., Philadelphia: Amer. Soc. for Testing and Materials, p. 35 (1988).

33. Hirschler, M. M. and G. F. Smith. *Eastern Section Combust. Inst. Fall Tech. Mtg.*, San Juan, Puerto Rico, paper 40 (1986).

34. Carroll, W. F., M. M. Hirschler and G. F. Smith, in *RETEC Conf. on "PVC: THE ISSUES*, Atlantic City, NJ, p. 76 (September 1987).

35. Burgess, W. A., R. D. Treitman and A. Gold. "Air Contaminants in Structural Firefighting," N.F.P.C.A. Project 7X008, Harvard School Public Health (1979).

36. Grand, A. F., H. L. Kaplan and G. H. Lee. "Investigation of Combustion Atmospheres in Real Fires," U.S.F.A. Project 80027, Southwest Research Institute (1981).

37. New York State Uniform Fire Prevention and Building Code–Art. 15, Part 1120 Combustion Toxicity Testing and Regulations for Implementing Building Materials and Finishes Fire Gas Toxicity Data File (1987).

38. Bukowski, R. W. *Fire Technol.*, 21:252 (1985).

39. Benjamin, I. A. *J. Fire Sci.*, 5:25 (1987).

40. McCaffrey, B. J., J. G. Quintiere and M. F. Harkleroad, *Fire Technol.*, 17:98 (1981).

41. Babrauskas, V. *Fire Technol.*, 16:94 (1980).

42. Thomas, P. H. *Fire Mats*, 5:103 (1981).

43. Lawson, J. R. and J. G. Quintiere, *Fire Technol.*, 21:267 (1983).

44. Anderson, R. C., P. A. Croce and J. D. Sakura. "Study to Assess the Feasibility of Incorporating Combustion Toxicity Requirements into Building Material and Furnishing Codes of New York State," A. D. Little, Inc., Reference 88712 (May 1983).

45. Alarie, Y., M. Matijak-Schaper and M. R. Stock. *Fire Sci. Technol.*, 1(1):10 (1982).

46. Carslaw, H. S. and J. C. Jaeger. "Conduction of Heat in Solids," 2nd ed. Oxford University Press, Oxford, p. 102 (1959).

Flammability Studies of 700 Articles of Upholstered Furniture

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ABSTRACT

In 1981 the Bureau of Home Furnishings and Thermal Insulation began a study to evaluate the potential for cigarette ignition of residential upholstered furniture and to determine the percent of compliance with California's mandatory flammability regulations for materials used in upholstered furniture and the State's labeling requirements. This paper reports the results on 700 articles of upholstered furniture. The presence of labels and compliance with California's furniture flammability regulations is discussed. A summary of cigarette ignitions is given. The effect of cigarette test location, cover fabric weight, fiber content, resin backcoating and type filling material on cigarette ignition is discussed and the wide variety of material choices for cigarette ignition resistant residential upholstered furniture demonstrated.

Key words: Flammability, furniture, smoldering, cigarettes, California, fabrics, substrates, resin backcoating, fabric weight, fabric content, upholstering.

INTRODUCTION

ALL NEW FURNITURE offered for sale in California must meet the flammability regulations of the California Bureau of Home Furnishings and Thermal Insulation, regardless of the place of manufacture.

0734-9041/88/02 0121–18 $04.50/0

Bureau inspectors have direct access to all manufacturing facilities within the state, and therefore can make on-site inspections and physically obtain representative samples for Bureau analysis. Bureau inspectors, however, do not inspect manufacturing plants outside California, so samples from out-of-state manufacturers must either be obtained from retailers or be sent by the manufacturer to the Bureau for analysis.

California law permits the Bureau to take from retailers such materials and articles as may be necessary for laboratory evaluation, without having to reimburse the retailer. To avoid causing financial hardship to furniture retailers within the state, the California legislature authorized the Bureau to budget for the purchase of upholstered furniture each year so that an ongoing testing program could be established.

Upholstered furniture acquired under this ongoing testing program since 1981 includes more than 700 upholstered articles representing a random cross section of style, price and retailer. The earlier phases of this program [1–7] included 450 articles most of which were manufactured in the United States. More recently, imported furniture from Europe and Asia has become a significant percentage of the furniture sold in California. During the 1985–1986 fiscal year, imported furniture was intentionally selected for sampling to determine compliance with California flammability and labeling regulations. The addition of a significant number of imported upholstered articles to the data base provided an opportunity to compare the relative degree of compliance of domestic and imported furniture with California flammability regulations.

This ongoing testing program has significantly increased the number of upholstered products in the data base, which now is probably the largest in the world. This paper presents information on 700 upholstered articles, and discusses the level of compliance with California flammability regulations and the effect of design factors such as style, and technical factors such as cigarette test location, fabric composition, fabric weight, backcoating, and stuffing material, on the cigarette resistance of furniture. These technical factors are of particular interest to manufacturers and suppliers of component materials and to furniture manufacturers.

PROCEDURE

Each piece of upholstered furniture obtained by the Bureau, was photographed and evaluated for compliance with the requirements of

Technical Bulletin 116, "Requirements, Test Procedures [illegible] Apparatus for Testing the Flame Retardance of Upholstered Furniture" [illegible] Although Technical Bulletin 116 is a voluntary standard in California, [illegible] it was of interest to determine what percentage of furniture was in fact resistant to cigarette ignition. Each piece was tested at multiple locations with cigarettes covered with 6 × 6-inch squares of cotton sheeting. Cigarettes were placed at each furniture location likely to be the resting place of a carelessly discarded cigarette. Such locations included crevices formed by the abutment of the [illegible] with backs and arms; welt cords; smooth furniture surfaces [illegible] seats, headrests, and backs of recliners; quilted and tufted [illegible] areas; tops of arms; and tops of backs (Figure 1).

In accordance with the requirements of Technical Bulletin [illegible] cigarette ignition of a given location was considered to have occurred if a char developed more than two inches in any direction from the cigarette, or open flaming occurred.

Following testing, the furniture was disassembled into its component parts and each type of filling material was weighed and chemically analyzed, and the location within the furniture was noted.

After the furniture was disassembled, the component filling materials and outer fabrics were tested for compliance with the mandatory requirements of Technical Bulletin 117, "Requirements, Test Procedures and Apparatus for Testing the Flame Retardance of Resilient Filling Materials Used in Upholstered Furniture" [9].

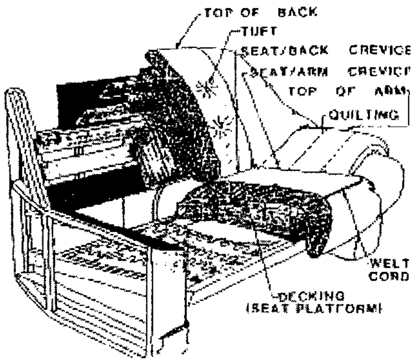


Figure 1. Cross section of chair/cigarette test locations.

When some of the components met the requirements and other components failed to meet the requirements, the Chief of the Bureau reviewed the test results in the light of the article construction and amount of substrate material present, and rendered a judgement as to whether the article essentially complied or failed to comply with flammability requirements.

At appropriate steps during this procedure, the furniture was checked for compliance with labeling requirements. All furniture sold in the United States must carry a law label correctly describing the contents. All furniture sold in California must also carry a flammability label showing compliance with California flammability regulations. In addition, some furniture carries a label showing compliance with the voluntary standard of the Upholstered Furniture Action Council (U.F.A.C.).

UPHOLSTERED PRODUCTS IN THIS STUDY

More than 700 upholstered products have been evaluated in this ongoing testing program since 1981. This data base of commercial upholstered products is probably the largest in the world. The number of articles evaluated in each fiscal year is shown below.

Fiscal Year	Number of Articles
1981–1982	171
1982–1983	143
1983–1984	99
1984–1985	74
1985–1986	70
1986–1987	110
1987–1988	33
Total	700

Testing of articles in Fiscal Year 1987–1988 is not complete.

Most of the products evaluated in Fiscal Years 1981–1985 and 1986–1988 were manufactured in the United States, and no effort was made at that time to analyze information about domestic and imported products separately. During the period prior to 1985, imports were not considered a significant percentage of the furniture sold in California.

Of the 70 articles evaluated in Fiscal Year 1985–1986, only two were manufactured in the United States and 68 were imported: 45 from

Italy, 15 from Taiwan, 3 from Denmark, 2 from Norway, and 1 each from Canada, Belgium, and Romania. This high percentage (97.1%) of imported furniture in this year's survey is the result of both increased imports and increased concern about the compliance of imported furniture with California flammability regulations. The percentage of imported furniture is therefore a factor which is dependent on the time period during which sampling occurred.

More detailed examination of the 70 articles evaluated in Fiscal Year 1985-1986 indicated that style and material were dependent on place of manufacture (Figure 2). Of the 45 articles imported from Italy, 40% had leather upholstery and 40% were dinette, steno, and office chairs and bar stools, styles with few crevices. Of the 15 articles imported from Taiwan, 33.3% had leather upholstery, and 53.3% were dinette, steno, and office chairs and bar stools, styles with few crevices. These imported products directed at specialized markets would not necessarily have the same response to ignition sources as products intended for broader markets since their physical shape and cover fabrics were different from the broad population of furniture. An apparent difference in the percentage of domestic and imported furniture which is cigarette resistant may really be a difference between style or materials.

Of the 700 upholstered products in this study, 698 upholstered products were tested according to Technical Bulletin 117. Polyurethane foam pads were contained in 695 products as stuffing material, shredded polyurethane foam in 58 products, cotton batting in 183 prod-

Country	# Tested	Style	% Furn. with leather
Italy	45	Dinette/steno/office/ barstools - 40%	40.0%
Taiwan	15	Dinette/steno/office/ barstools - 53.3%	33.3%
Denmark	3	Swivel recliner/ armchair/chair	33.0%
Norway	2	Steno/ottoman	100.0%
Canada	1	Rocker	0.0%
Belgium	1	Armchair	100.0%
Romania	1	Dinette	0.0%

Figure 2. Foreign manufactured articles.

Distribution of Substrates 700 Articles (1981/88)	
Type of Substrate	% of Furn. Containing Substrate
PU Foam Pads	99.3%
Shredded PU Foam	8.3%
Cotton Batting	26.1%
Cellulose Fiber Pads	3.3%
Hair/Veg. Fiber Pads	0.1%
Syn. Fiber Bat./Pads	64.0%
Cotton/Syn. Pads	35.4%

Figure 3. Substrate distributions.

Cigarette Test Locations 679 Articles (1981/88)		
Location	# of Cig Tests	(%)
Smooth surfaces	2096	(28.0%)
Deckings	1019	(13.6%)
Welts Cords	723	(9.6%)
Crevices	1613	(21.5%)
Quilted surfaces	95	(1.3%)
Tufted surfaces	410	(5.5%)
Tops of backs	563	(7.5%)
Tops of arms	974	(13.0%)
Total	7493	(100.0%)

Figure 4. Cigarette test locations.

ucts, cellulose fiber pads in 23 products, hair/vege[illegible] 1 product, synthetic fiber battings and pads in 448 produ[illegible] blended cotton/synthetic battings and pads in 248 products (Figure 3). Note that performance of an article when tested to Technical Bulletin 117 is not necessarily an accurate predictor of cigarette ignition resistance.

Six hundred and seventy-nine of the 700 upholstered articles in this study were tested for resistance to cigarette ignition according to Technical Bulletin 116. Of the 7,493 locations at which cigarette tests were performed (Figure 4), 2,096 were on smooth surfaces, 1,019 on decking areas, 723 on welt cords, 1,613 on crevices, 95 on quilted surfaces, 410 on tufted surfaces, 563 on tops of backs, and 974 on tops of arms. Of the 678 upholstered products for which cover fabrics were identified, 89 articles had 100% cellulosic fiber, 294 had cellulosic/thermoplastic fiber blends of various compositions and 256 had 100% thermoplastic fiber. Leather, an animal material which is neither cellulosic nor thermoplastic, was the cover fabric in 39 articles.

RESULTS

Among the 700 upholstered products in this study, 92.4% had law labels, 10.6% had Technical Bulletin 116 labels, 58.5% had Technical Bulletin 117 labels, and 25.6% had U.F.A.C. labels (Figure 5).

Articles evaluated in Fiscal Year 1985–1986 provided the largest data base of imported articles. Of the 45 articles imported from Italy, 33 (73.3%) had law labels but only 16 (35.5%) had correct law labels; 28 (62.2%) had flammability labels, and none had U.F.A.C. labels. Of the 15 articles imported from Taiwan, 11 (73.3%) had law labels but only 7 (46.6%) had correct law labels; 9 (60%) had flammability labels, and none had U.F.A.C. labels.

Six hundred and seventy-nine upholstered articles in this study were tested for resistance to cigarette ignition according to Technical Bulletin 116 and the compliance rate for all years was 70.7% based on strict adherence to criteria. This number includes articles where only deckings failed the cigarette standard. This was the average of a generally rising trend in cigarette resistance, 57.3% in 1981–1982, 62.9% in 1982–1983, 69.7% in 1983–1984, 81.1% in 1984–1985, 91.5% in 1985–1986, 79.4% in 1986–1987, and 90.3% in 1987–1988 (Figure 6). These percentages may not, however, represent the exact percentage of furniture sold in California which is cigarette resistant, since they are based on test data only.

Thirty-seven of the 45 articles imported from Italy were tested for

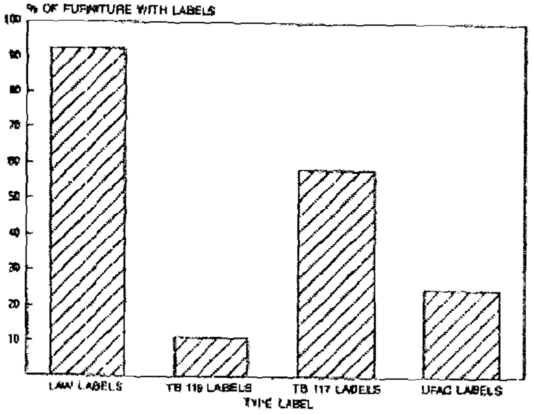


Figure 5. Presence of labels.

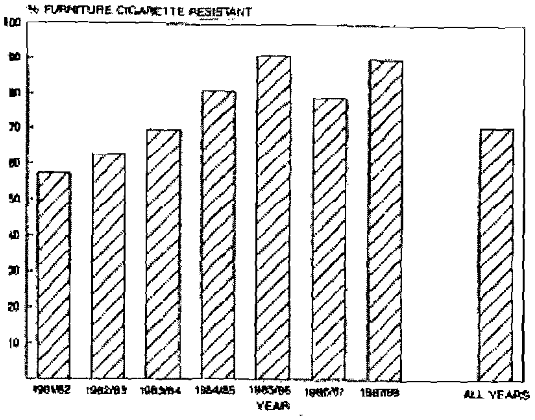
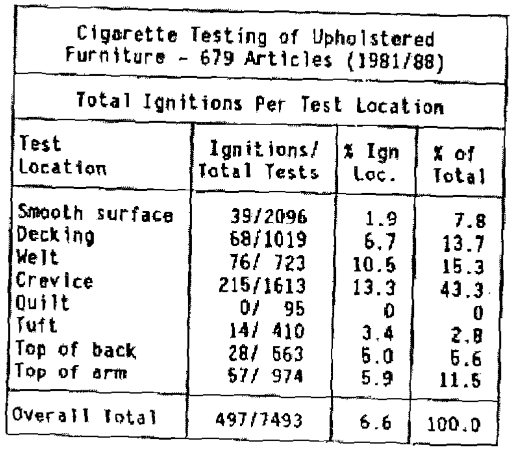


Figure 6. Cigarette resistance compared by year.



Cigarette Testing of Upholstered Furniture - 679 Articles (1981/88)

Total Ignitions Per Test Location

Test Location	Ignitions/ Total Tests	% Ign Loc.	% of Total
Smooth surface	39/2096	1.9	7.8
Decking	68/1019	6.7	13.7
Welt	76/ 723	10.5	15.3
Crevice	215/1613	13.3	43.3
Quilt	0/ 95	0	0
Tuft	14/ 410	3.4	2.8
Top of back	28/ 563	5.0	5.6
Top of arm	57/ 974	5.9	11.5
Overall Total	497/7493	6.6	100.0

Figure 7. Cigarette ignition frequency at test locations.

compliance with Technical Bulletin 116, and 89.8% passed. Of the 15 articles imported from Taiwan, 14 were tested for compliance with Technical Bulletin 116, and 100% passed. It should be noted, however, that more than 80% of the articles imported from Italy and Taiwan either had leather upholstery, which is generally resistant to cigarette ignition, or were styles with few crevices and therefore less vulnerable to cigarette ignition. Domestic articles did not have the same material and style distribution.

The different locations on which cigarette tests were performed according to Technical Bulletin 116 were studied for frequency of ignition (Figure 7). Cigarette ignition occurred most frequently on crevices (13.3% of these locations), followed by welt cords (10.5%), decking areas (6.7%), tops of arms (5.9%), tops of backs (5.0%), tufted surfaces (3.4%), smooth surfaces (1.9%), and quilted surfaces (0%), with an overall average frequency of 6.6%.

Of the 679 upholstered articles tested for resistance to cigarette ignition according to Technical Bulletin 116, 70.7% had no ignition, 8.5% had one ignition, 7.4% had two ignitions, 7.7% had three ignitions, and 5.7% had more than three ignitions (Figure 8). 12.4% had ignitions in one type of test location, 10.2% in two types of test locations, 4.0% in three types, and 2.8% in more than three types (Figure 9).

Cigarette Testing of 679 Upholstered Articles - TB 116 (1981/1988)		
Article Performance Per # of Ignitions		
# of Ignitions	# of Articles	Percent Articles
0	480	70.7
1	58	8.5
2	50	7.4
3	52	7.7
>3	39	5.7
	679	100.0

Figure 8. Number of ignitions per article.

Cigarette Testing of 679 Upholstered Articles - TB 116 (1981/1988)	
Article Performance Per Type of Test Location	
# of Types of Test Loc. where Ign. occurred	Number and Percent of Articles
0	480 (70.7%)
1	84 (12.4%)
2	69 (10.1%)
3	27 (4.0%)
>3	19 (2.8%)
	679 (100.0%)

Figure 9. Number of types of cigarette test locations with ignitions.

Fiber content of upholstery fabric has long been considered an important factor in resistance to cigarette ignition. Six hundred seventy-nine upholstered articles tested according to Technical Bulletin 116 in this study were used in quantifying this effect (Figure 10). Articles with fabrics which were 100% thermoplastic were the most resistant (87.7%) to cigarette ignition. Articles with fabrics which were 100% cellulosic were the least resistant (32.6%) to cigarette ignition, with heavier fabric weights (12 or more oz./sq. yd.) being less resistant (15.6%) and lighter fabric weights (less than 12 oz./sq. yd.) being more resistant (42.1%). Leather was the upholstery fabric most resistant to cigarette ignition (94.9% for all fabric weights), although 2 leather articles did experience cigarette failures due to surface burning in finger patterns across the fabric. Thermoplastic fabrics included synthetic fibers such as acrylic, polyester, polyvinyl chloride, nylon, polypropylene and acetate and smolder resistant natural protein fibers, wool and silk. Cellulosic fabrics included cotton, rayon and linen.

Six hundred and seventy-eight upholstered articles tested according to Technical Bulletin 116 and analyzed for fabric composition were divided into groups according to fiber content (0 to 29, 30 to 69, and 70 to 100 percent cellulosic) and fabric weight (less than 12 oz./sq. yd. and 12 or more oz./sq. yd.) (Figure 11).

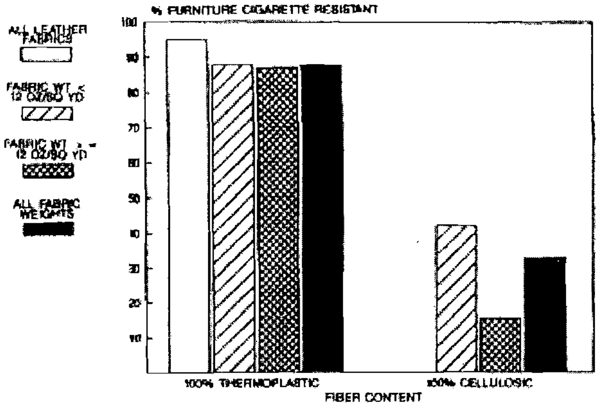


Figure 10. Effect of fiber content and weight on ignition (100% thermoplastic/100% cellulosic).

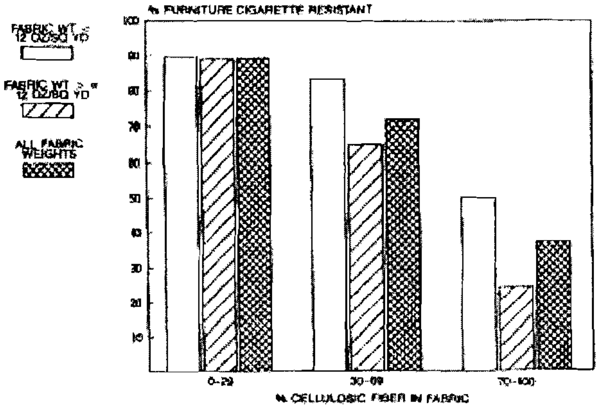


Figure 11. Effect of fiber content and weight on ignition (0–29%/30–69%/70–100% cellulosic).

Fabrics with the lowest cellulosic content (0 to 29%) were the most resistant (89.3%) to cigarette ignition. Cellulosic/thermoplastic blend fabrics in the range of 30 to 69% were less resistant to cigarette ignition (71.9%), with the lower resistance of heavier fabrics becoming more significant (65.0% compared to 83.3%). Predominantly (70% to 100%) cellulosic fabrics were the least resistant to cigarette ignition (37.3%), with the lower resistance of heavier weight fabrics even more significant (24.4% compared to 50.0%). 100% cellulosic fabrics had the lowest resistance to cigarette ignition (32.6%), with heavier weight fabrics much less resistant (15.6%) than lighter weight fabrics (42.1%). Heavier weight cellulosic fabrics may be more prone to develop the char structure needed to support smoldering combustion, since they contain more fuel per unit area. Also, since unscoured cellulosic fabrics contain high concentrations of alkali metal ions which are known to promote smoldering, the heavier cellulosics may be even more prone to smolder than lighter fabrics due to the larger amounts of alkali ions present [10]. However, no actual research was conducted in this study to correlate char formation or alkali metal ion content to smoldering performance.

The strong effect of cellulosic fiber content in the upholstery fabric was so evident when the fabrics were divided into three groups according to cellulosic content, that the fabrics were divided into smaller groups of 10% increments of cellulosic content in order to study this effect in greater detail (Figure 12). When cellulosic content is considered as the principal factor, there seemed to be three distinct ranges of cellulosic content with regard to resistance to cigarette ignition. 88.3 to 96.3% resistance was observed from 0 to 29% cellulosic, 63.2 to 80.0% resistance from 30 to 79% cellulosic, and 15.6 to 31.5% resistance from 80 to 100% cellulosic. The incorporation of thermoplastic fiber in the upholstery fabric appears to impart good to moderate resistance to cigarette ignition until the cellulosic fiber content reaches and exceeds 80%. The mechanism involved may be interference of the thermoplastic with the formation of the char structure needed to support smoldering, but this was not investigated in this study.

Six hundred and seventy-four of the upholstered articles tested for resistance to cigarette ignition were analyzed for content of fabric resin backcoating (Figure 13). The average fabric resin backcoating content was 11.6% in 178 articles which were not smolder resistant. The average fabric resin backcoating content in the 496 articles which passed was 18.1%. Articles which passed included 20 articles with failures at the decking location only, since no resin analysis was performed on the decking fabrics. Articles with higher fabric resin backcoating content tended to be more resistant to cigarette ignition. However, this effect

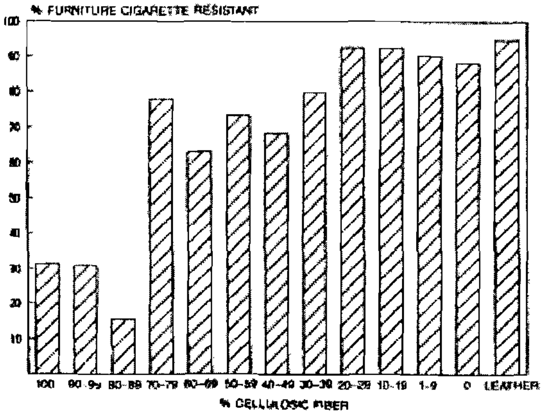


Figure 12. Effect of fiber content (10% cellulosic increments).

Effect of Resin Backcoating
674 Articles (1981/1988)

Number of Articles	Average Resin Backcoating
496 Cigarette Resistant Articles	18.1%
178 Non-Cigarette Resistant Articles	11.6%
674 Articles	16.4%

Figure 13. Effect of resin backcoating on ignition.

may be partially the effect of fiber content. Some thermoplastic fabrics which are more resistant to smoldering, such as polypropylene, tend to require use of resin backcoatings more than cotton fabrics, which are less resistant to smoldering. The nature of the substrate beneath the upholstery fabric is a factor in the resistance of the upholstered furniture to cigarette ignition (Figure 14). Among the 698 upholstered articles in this study for which the stuffing material was analyzed, 99.6% contained polyurethane foam pads, 8.3% contained shredded polyurethane foam, 26.2% contained blended cotton batting, 3.3% contained cellulose fiber pads, 0.1% contained hair/vegetable fiber pads, 64.0% contained synthetic fiber batting and pads, and 35.5% contained blended cotton/synthetic fiber pads. The total of these numbers exceeds 100% because most articles contained more than one type of stuffing material.

To assess the effect of substrate type on smoldering performance, the population of articles not resistant to cigarette ignition was compared to the entire population of articles both resistant and nonresistant, with particular attention to the substrates present directly below upholstery fabrics in each article population.

While 99.6% of all articles tested in the study contained polyurethane foam pads, only 82.4% of the smolder-prone articles contained this substrate at a failure location. Similarly, while 64.0% of all articles contained synthetic fiber battings and pads, only 53.8% of smolder-prone articles contained this substrate, at a failure location. Of the small percentage of articles containing shredded polyurethane foam (8.3%) and cellulose fiber pads (3.3%), only 3.5% and 3.0% of the

smolder-prone articles respectively contained these substrates at failure locations. Thus the presence of polyurethane foam pads, shredded foams, or synthetic battings at a cigarette test location tended to decrease the probability of smoldering, without consideration of any other factors, and cellulose fiber pads, in the amounts tested, had little effect.

Blended battings containing mixtures of cellulosic and synthetic fiber were present in 35.4% of all articles but were present at failure locations in 39.2% of the smolder-prone articles. Likewise, blended cotton battings were present in 26.1% of the articles but in 34.2% of the smolder-prone articles at failure locations. One hundred and forty-seven (73.9%) of the 199 smolder-prone articles contained substrates containing cellulosic fiber. Thus, blended cotton/synthetic battings and pure cotton battings tended to increase the probability of smoldering, when present at cigarette locations.

A comparison of substrates at cigarette failure locations to substrates at cigarette resistant locations only might have produced an even more pronounced effect, but was not investigated.

Fifty-two articles which were not cigarette resistant, and did not contain cotton batting, cellulose fiber pads, or blended cotton/synthetic batting as underlying substrate at failure locations, were further investigated to determine what additional factors contributed to their

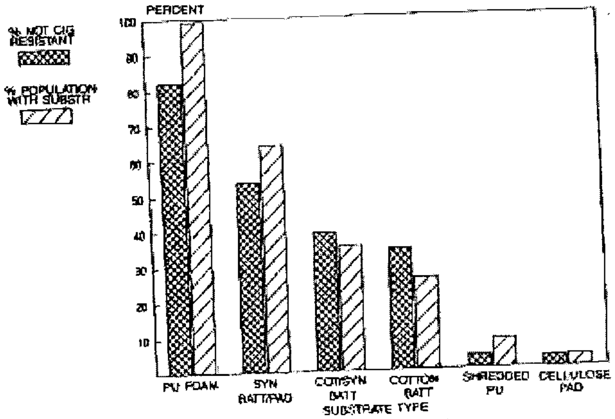


Figure 14. Substrate effects on ignition.

propensity to smolder. Twenty-two of these articles (42.3%) contained 100% cellulosic fabric, 20 articles (38.5%) contained cover fabrics containing between 50 and 99% cellulosic fiber, 8 articles (15.4%) contained fabrics having 1 to 49% cellulosic fiber, 2 articles (3.8%) contained leather fabric only and none contained 100% thermoplastic fabrics. In addition, 28 of these 52 articles contained fabrics having weights equal to or greater than 12 ounces per square yard, and 34 had fabrics with no resin backcoating. Twenty articles contained 100% cellulosic fabrics and no resin backcoating with an average fabric weight of 10.1 ounces per square yard. Thus, even in the absence of a cellulosic substrate, presence of a cellulosic fabric, especially heavier-weight fabrics, tended to be a causative factor in smoldering.

CONCLUSIONS

Results of this ongoing testing program show a general trend of increasing resistance to cigarette ignition in commercial upholstered furniture products sold in California as a result of changes in fabrics, substrates and construction styles by manufacturers. The samples selected are representative of the broad spectrum of products available.

The large number of upholstered articles in this study, probably the largest data base of its kind in existence, provides the most authoritative basis for determining the relative importance of various factors in the resistance to cigarette ignition of commercial upholstered furniture. This resistance to cigarette ignition is defined by tests according to Technical Bulletin 116 for upholstered articles and Technical Bulletin 117 for their components.

The cellulosic content of the upholstery fabric appears to be the single most important factor in resistance to cigarette ignition. Resistance was greatest when cellulosic content was 0 to 29%, less when cellulosic content was 30 to 79%, and lowest when cellulosic content was 80 to 100%. The incorporation of thermoplastic fiber in the upholstery fabric appears to impart resistance to cigarette ignition until the cellulosic content exceeds approximately 80%.

For upholstery fabrics with high cellulosic content, fabric weights of 12 or more oz./sq. yd. provided less resistance to cigarette ignition than fabric weights less than 12 oz./sq. yd. The heavier weight cellulosic fabrics appear to be more susceptible to cigarette ignition.

Higher resin backcoating contents in the upholstery fabrics appeared to be associated with greater resistance to cigarette ignition. This effect may be partially the effect of fiber content, because thermoplastic fabrics tend to have more resin backcoating.

The substrate beneath the upholstery fabric appears to be a contributing factor in resistance to cigarette ignition. As a substrate, cotton batting and blends containing cotton fibers appeared to increase the probability of ignition, and polyurethane foam and polyester fiber batting appeared to decrease the probability of ignition.

Resistance to cigarette ignition for a particular article is generally independent of country of origin and more likely to be related to style and shape of article, type and weight of fabric used, amount of resin backcoating and the nature of the underlying substrate.

Smoldering cigarette ignition is most likely to occur in the crevice area of an upholstered article containing a heavy weight fabric which is 100% cellulosic fiber, with no resin backcoating and a blended cotton batting substrate directly beneath the fabric.

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REFERENCES

1. Damant, G. H. "Flammability Aspects of Upholstered Furniture," *Proceedings of the International Conference on Fire Safety*, Univ. of San Francisco (January 12–16 (1976).
2. Damant, G. H., J. A. McCormack and S. S. Williams. "California Enforcement Tests on Commercial Chairs," *Proceedings of the International Conference on Fire Safety*, 7:2–10 (1982).
3. Damant, G. H., J. A. McCormack and S. S. Williams. "Flammability Studies of Upholstered Furniture," *Proceedings of the International Conference on Fire Safety*, 8:1–11 (1983).
4. Damant, G. H., S. S. Williams and J. A. McCormack. "The Role of Fabric in the Cigarette Ignition of Upholstered Furniture," *Journal of Fire Sciences*, 1(5):309–321 (September/October 1983).
5. Williams, S. S., J. A. McCormack and G. H. Damant. "Upholstered Furniture Flammability: Test Results on 266 Commercial Chairs," *Proceedings of the International Conference on Fire Safety*, 9:1–2 (1984).
6. J. A. McCormack, G. H. Damant and S. S. Williams. "Cigarette Evaluation of 450 Pieces of Residential Upholstered Furniture," *Proceedings of the International Conference on Fire Safety*, 11:1–15 (1986).

7. McCormack, J. A., G. H. Damant and S. S. Williams. "Cigarette Evaluatio of 450 Pieces of Residential Upholstered Furniture," *Journal of Fir Sciences*, 4(2):135–147 (March/April 1986).

8. California Bureau of Home Furnishings Technical Bulletin 116 "Require ments, Test Procedure and Apparatus for Testing the Flame Retardance o Upholstered Furniture" (January 1980).

9. California Bureau of Home Furnishings Technical Bulletin 117, "Requirements, Test Procedure and Apparatus for Testing the Flame Retardance of Resilient Filling Materials Used in Upholstered Furniture" (January 1980).

10. Ihrig, A. M., A. L. Rhyne, V. Norman and A. W. Spears, (Lorillard Research Center, Greensboro, NC), "Factors Involved in the Ignition of Cellulosic Upholstery Fabrics by Cigarettes," *Journal of Fire Sciences*, 4(4):237–260 (July/August 1986).

Thermal Stability of Fire Retardants:* III, Decomposition of Pentabromochlorocyclohexane and Hexabromocyclododecane under Processing Conditions

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ABSTRACT

The thermal decomposition kinetics of several aliphatic FR agents containing vicinal bromines were studied under temperature conditions, i.e., 200–226°C., commonly found in extruders. The reactions were monitored by the rate of HBr evolution and by the formation of trans-stilbene in dilute (1.8–10 wt.% agent) bibenzyl solutions. The measured reaction rate constants (k_{HBr}) were found to include a free radical component (k_{HBr_1}) and an ionic component (k_{HBr_2}) resulting from the homolytic cleavage of a carbon-bromine bond and from an iron or zinc induced reaction, respectively.

Of the primary agents used in polystyrene, pentabromochlorocyclohexane was found to decompose at about three times the rate of hexabromocyclododecane at any given temperature.

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*The use of the terms fire retardant and FR in this document is not intended to reflect hazards presented by these or any other materials under actual use conditions.

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FIRE AND MATERIALS, VOL. **21**, 123–141 (1997)

Comparison of the Propensity of Cigarettes to Ignite Upholstered Furniture Fabrics and Cotton Ducks (500-Fabric Study)

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The present study investigates the validity of a test method for smoldering cigarette ignition propensity of upholstery fabrics based on using 'cotton duck' fabrics, and proposed by NIST. A comparison was made between the ignition propensity of cigarettes as assessed by (1) a set of 500 upholstery fabrics (chosen at random among typical upholstery fabrics) and (2) a test method proposed by NIST (NIST 851), and based on 'cotton duck' fabrics. The set of 500 fabrics can be assumed to be a representative cross-section of the upholstery fabrics available in the early 1990s, while the 'cotton duck' fabrics are not typical upholstery fabrics, and it was unclear whether they would behave similarity or differently from upholstery fabrics. Of the 500 fabrics tested, only 145 fabrics were ignitable by cigarettes, all of them predominantly (or completely) cellulosic. This study found that the overall results obtained from the 500-upholstery fabric study correlate well with those of the 'cotton duck' study. Therefore, the 'cotton ducks' can be considered, as a whole, to behave similarly to the majority (estimated at perhaps 80%) of the upholstery fabrics available at the time of the study, and the test is valid. In this study it was also found that the 'cotton duck' test method correlated well with an earlier cigarette ignition test method, shown to be a good predictor of full-scale upholstered furniture cigarette ignition results, when using a set of five cigarettes. Finally, a fabric density threshold was found, above which the percentage of ignitions of cellulosic fabrics, the percentage of cellulosic fabrics that are ignitable and the flame spread rate of fabrics in a flaming ignition test are all unaffected. © 1997 by John Wiley & Sons, Ltd.

Fire and Materials, Vol. **21**, 123–141 (1997) (No. of Figures: 7 No. of Tables: 8 No. of References: 24)

WORK OBJECTIVE

The present work compares the complete results of two experimental projects to investigate whether the NIST 851 test is a valid method for assessing cigarette ignition propensity of upholstery fabrics. This is done by correlating the results of tests on the same five cigarettes with the NIST test and with 500 fabrics, assumed to be a representative cross-section of the upholstery fabrics available in the early 1990s.

BACKGROUND ON CIGARETTE IGNITION TESTING

The problem of fire and furniture has been under investigation for many years, and has been the subject of much work.[1–3] This is primarily because it has been shown that upholstered furniture and bedding products represent a disproportionate share of the items first ignited which lead to fatalities in residential fires.[4–7] The most common ignition source for these fires tends to be classified as 'smokers' materials', which can mean cigarettes, matches or lighters. Thus, this category is further subdivided into smoldering ignition (cigarettes) and flaming ignition (other sources).

In the 1970s a pair of fire test methods were developed to address the issue. They dealt with ignition of fabrics by smoldering cigarettes. These test methods eventually were standardized as ASTM E1532[8] and ASTM E1353.[9] The objective of the test methods mentioned was to investigate whether fabrics and foams could be ignited by cigarettes, and they used a 'standard' cigarette as the smoldering ignition source.

More recently, a test method has been developed[10,11] to assess the propensity of cigarettes to ignite fabrics in upholstered furniture composites. However, that test method uses a set of three cellulosic fabrics (cotton ducks) as surrogates for upholstered furniture fabrics. It has been stated that these fabrics are significantly different in several respects from the typical upholstery fabric.

In 1984 the United States Congress recognized that there was a need to reduce the propensity of cigarettes to ignite upholstered furniture composites, which would be a more effective way of dealing with the problem than by addressing the furniture items. Thus Congress passed the Cigarette Safety Act of 1984,[12] and entrusted a Technical Study Group (TSG), chaired by Dr Richard G. Gann, of the National Institute of Standards and Technology (NIST) (at that time, the National Bureau of Standards), with the responsibility to 'undertake such studies and other activities as it considers necessary and appropriate to determine the technical and commercial feasibility,

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economic impact, and other consequences of developing cigarettes and little cigars that will have a minimum propensity to ignite upholstered furniture or mattresses. Such activities include identification of the different physical characteristics of cigarettes and little cigars which have an impact on the ignition of upholstered furniture and mattresses, an analysis of the feasibility of altering any pertinent characteristics to reduce ignition propensity, and an analysis of the possible costs and benefits, both to the industry and the public, associated with any such product modification.' The work was sponsored by the Consumer Product Safety Commission (CPSC) at the Center for Fire Research of NBS, and involved six parts:

(1) Testing of commercial cigarettes, in order to determine the extent to which available cigarette packings vary in their propensity to ignite soft furnishings.
(2) Measurements of ignitability, in order to review the state of the art of such measurements, to identify those characteristics of cigarettes which affect ignition propensity, to investigate patents for reducing ignition propensity and to develop an understanding of the thermal phenomena and a model of the ignition process.
(3) Test method development, to generate a laboratory bench-scale test method for measuring ignition propensity of cigarettes.
(4) Assessment of quality assurance of experimental cigarettes, to investigate the composition and statistical variation of experimental cigarettes obtained from the tobacco industry.
(5) Assessment of effects of alkali ions in fabrics and fillings, to investigate their potential effect on susceptibility to ignition of the soft furnishings.
(6) Conduction of full-scale furniture tests, to validate the bench-scale test method data using real furniture items.

The work of the TSG resulted in an overall summary[13] and a series of publications, the most relevant of which, to the present work, analysed the technical problem to be solved, and recommended the steps to be taken.[14,15] One of the most important issues analysed by the TSG were the factors most crucially affecting the ignition propensity of cigarettes towards upholstery fabrics. The factors considered were physical or chemical parameters that can be controlled during the manufacture of commercial cigarettes. For that purpose 32 cigarettes were manufactured ('100 Series'), and characterised well, wherein a number of parameters were varied broadly, including: type of tobacco, packing density of the tobacco in the cigarette column (or use of expanded tobacco), permeability of the cigarette paper, use of citrate additives in the paper, and circumference of the cigarette. The work done concluded that paper permeability, tobacco packing density, cigarette circumference and presence of citrate all affected the ignition propensity of cigarettes, when varied with all other properties remaining equal.

Following the publication of this work, Congress passed the Fire Safe Cigarette Act of 1990,[16] and a Technical Advisory Group (TAG) was formed, again under the chair of Dr Gann. At the request of the TAG, CPSC sponsored NIST to conduct research with three goals:

(1) Development of a viable standard test method to assess cigarette ignition propensity.
(2) Compilation of performance data for cigarettes using that test method.
(3) Conducting laboratory studies and computer modeling to develop predictive capabilities.

At the same time, the CPSC was charged with:

(1) Conducting a study to collect data about characteristics of cigarettes, products ignited and smokers involved in fires.
(2) Development of information on societal costs of cigarette-initiated fires.
(3) Development of information, together with the Department of Health and Human Services, on changes in toxicity of smoke and other health effects of new cigarette prototypes with reduced ignition propensity.

The TAG also issued a final report,[17] and one of its parts presented a proposed test method,[11] later published in a peer-reviewed journal[10] (this method will be referred to in this work as the NIST 851 test, reflecting the number of the NIST publication, since NIST does not number its methods). In fact, after investigations of several surrogate methods, NIST developed both a surrogate test method (the Cigarette Extinction Test) and a test method involving the use of upholstered furniture composites (or mock-ups) and of cigarettes, which is the one addressed further in this work. Cigarettes were used to attempt ignition of three cellulosic fabrics (known as 'cotton ducks', representing a range of capabilities of being ignited, one of which was modified by adding a strip of plastic, to further broaden the ignitability range) all wrapped around the same type of foam.

The TAG chose a set of three cotton fabrics, known as 'cotton ducks', as the substrates for their mock-up cigarette ignition propensity test. The fabrics were chosen because of two advantages: (1) they are 100% cellulosic (which makes them more likely to be ignited by cigarettes, even with plastic substrates), and (2) they have long-term availability at a consistent level of quality (because they are used by the armed forces for tents and other applications), while traditional upholstery fabrics are replaced approximately every 6 months (because of fashion concerns). The disadvantages are that they are not traditional upholstery fabrics, in that they tend to have high weight per unit area, low porosity and high content of ions (principally alkali cations). The real issue, however, is to determine whether the 'cotton ducks' would predict similar ignition propensity for cigarettes as a random sampling of upholstery fabrics, and that is what is being done in this work.

Experience with this type of test method has long shown that smoldering ignition of fabrics is highly variable, and requires replication to obtain satisfactory results. A comparison between the repeatability and reproducibility of test methods for smoldering ignition of upholstery has also been conducted and is the subject of separate work.[18]

EXPERIMENTAL

Four tests were used as the basis for this work: (1) TSG fabric test,[14,15] (2) TAG cotton duck fabric test,[10,11] (3) Cigarette Ignition Propensity Joint Venture fabric test,[19] and (4) a surrogate extinction method proposed by the TAG.[11]

In the TSG test, a piece of fabric is laid on a 25 mm thick layer of polyurethane foam (Olympic foam #2715, 24 kg m^{-3} {1.5 lb ft^{-3}} density) inside a chamber, in a quiescent atmosphere (60% relative humidity, 24°C), and held in place with a metal frame. A cigarette is lit, allowed to smolder until 15 mm of rod has burned, and then placed on the fabric. The fabric is deemed to ignite if its charring extends at least 10 mm beyond the normal discoloration caused by the smoldering cigarette. Six replicates were run for each cigarette and each fabric.

In the NIST 851/TAG test, each cigarette is assessed with three cotton duck fabrics: #10, #6 and #4 (see Table 1, for fabric properties). The fabrics are placed on a polyether polyol polyurethane foam (32 kg m^{-3} {2.0 lb ft^{-3}} density). The resistance to ignition resistance of the substrates used increases from cotton duck #10 through cotton duck #6 to cotton duck #4. A thin polyethylene film (0.13 mm thick, 0.15 g cm^{-2} {44 oz yd^{-2}} density) is added as a heat sink to cotton duck #4, to make the mock-up more ignition resistant. Results of all three fabrics are averaged. A large number of replicates (at least 24) are run for each cigarette.

The method proposed by the Cigarette Ignition Propensity Joint Venture, used on all 500 fabrics, differs from the TSG test mainly in that a plastic box with four compartments is used, allowing six cigarettes each to be tested on four fabrics simultaneously.

The five cigarettes used are designated by arbitrary numbers (519, 506, 508, 525 and 528), which indicate that they are part of the '500 series' of 32 cigarettes made to represent a wide variation in variables. The main cigarette properties are described in Table 2.

DATA ANALYSIS

Representatives of the Cigarette Ignition Propensity Joint Venture, representing the tobacco manufacturing industry (Joint Venture), bought 500 upholstery fabrics, apparently at random, in the High Point, NC, area (which is the center of the upholstery industry).[19,20] They then proceeded to test the fabrics for ignitability by cigarettes. Interestingly, the fabrics can be subdivided into categories, based on the three properties described above, for example as proposed by A.W. Spears[21] (Table 3).

Appendix A contains all the physical information on the 500 fabrics chosen. On this basis, the fabrics can be classified into four categories: NIST Like-1, NIST Like-2 (excluding NIST Like-1 ones), NIST Unlike and Others, as shown in Table 4. Table 4. Table 4 does not contain the fabrics that are neither NIST Like nor NIST Unlike, which are the majority (384 out of the 500). The table contains 21 fabrics classified as NIST Like-1, 15 fabrics classified as NIST Like-2 and 82 classified as NIST Unlike. It must be noted, however, that three fabrics are classified as both NIST Like-2 and NIST Unlike: fabrics #107, 264 and 363.

The Joint Venture continued its investigation by using one cigarette, designated #519, and attempting the ignition of all fabrics, by means of a mock-up unpholstered furniture procedure,[19] similar to the TSG test.[14,15] The cigarette was chosen because it contains all four characteristics known to be crucial in increasing ignition propensity of cigarettes:[14,15,22] non-expanded tobacco, high

Table 1. Properties of cotton duck fabrics, polyethylene film and polyurethane foam

	Density kg m^{-2} (oz yd^{-2})	Porosity $\text{m}^3\text{s}^{-1}\text{m}^{-2}$ (Coresta units)	Potassium ppm
Cotton duck #10	0.50 (14.7)	$10.2–20.4 \times 10^{-3}$ (500–1,000)	ca. 4300
Cotton duck #6	0.72 (21.2)	$5.1–10.2 \times 10^{-3}$ (250–500)	ca. 5300
Cotton duck #4	0.83 (24.5)	$5.1–10.2 \times 10^{-3}$ (250–500)	ca. 4500
Polyethylene	1.50 (44)		
Foam	32 kg m^{-3} (2.0 lb ft^{-3})		

Note: porosity was measured in metric units, using Federal Method 5450, at a pressure drop of 1.27 cm of water, and the conversion to Coresta units assumes that the results vary proportionally with pressure drop, which is uncertain.

Table 2. Description of experimental cigarettes used

Cigarette #	Cigarette designation	Tobacco type	Expanded tobacco?	Paper porosity	Cigarette circumference (mm)	Citrate in paper?
519	BNHC25	Burley	No	High	25	Yes
506	BELN21	Burley	Yes	Low	21	No
508	BEHN21	Burley	Yes	High	21	No
525	FNLC25	Flue-cured	No	Low	25	Yes
528	FNHN25	Flue-cured	No	High	25	No

Table 3. Classification of fabrics by physical characteristics

Characteristic Units	Sodium + potassium ppm	Density oz yd^{-2}	Porosity Coresta Units
Cotton duck fabrics[a]	4327–5293	15–24	425–650
NIST Like-1 fabrics	> 1800	> 15.5	< 7000
NIST Like-2 fabrics[b]	> 1600	> 14	< 7000
NIST unlike fabrics	800–1800	9.5–15.5	–

[a] Data as reported by Spears.[21]
[b] NIST Like-2 Fabrics exclude those classified as NIST Like-1 Fabrics.

Table 4. Classification of all fabrics by properties, not by Ignitability

Fabric numbers

NIST Like-1	NIST Like-2	NIST Unlike	NIST Unlike	NIST Unlike	NIST Unlike
15	1	4	107	254	407
40	14	6	111	255	411
42	37	23	112	259	412
46	78	25	116	263	413
66	107	27	123	264	415
67	108	30	126	265	423
68	146	31	128	268	427
70	147	32	134	279	430
74	148	36	135	282	431
81	151	39	139	285	437
86	155	43	142	287	447
87	262	48	143	289	448
120	264	49	149	290	458
122	302	53	152	293	459
129	363	54	159	314	460
131		69	164	363	465
140		77	166	380	467
245		89	234	390	468
256		98	237	399	499
283		101	248	401	
419		102	251	406	

cigarette circumference, high paper porosity and citrate in the paper. A total of 145 fabrics had at least one ignition with cigarette 519, while the other 355 fabrics had no ignitions and were discarded. All remaining fabrics (i.e. the 145 that had ignitions) were then subjected to ignition using four additional cigarettes, designated numbers 506, 508, 525, and 528. Appendix B illustrates the percentage of ignitions obtained with each fabric, on each cigarette. The overall ranking of the five cigarettes used, by the use of the 500 fabrics is as follows, in order of increasing ignition propensity:

$$506 < 508 < 528 < 525 < 519$$

These fabrics can now be classified into the categories described above: 21 of the ignitable fabrics are NIST Like-1 (14%), 14 of the fabrics are NIST Like-2 (10%), 24 are NIST Unlike (17%) and 88 fabrics are neither NIST Like nor NIST Unlike (61%). It must be noted that two of the ignitable fabrics (#107 and #264) are both NIST Like-2 and NIST Unlike. The third fabric that was both NIST Like-2 and NIST Unlike (#363) was not ignited by cigarette #519, and was not used further.

Spears[21,23] also tested the same five cigarettes using the cotton ducks, with the NIST 851 test method.[10,11] As a consequence, it is now possible to analyse the results obtained when testing for ignition propensity using the various fabrics, and compare them with the results obtained using the cotton ducks. The results, shown in Table 5, indicate that NIST Like-1 and NIST Like-2 fabrics give similar results and rankings to the ones by the cotton ducks, and that NIST Unlike fabrics give somewhat different results. However, in spite of the differences, all sets of fabrics classify cigarette 519 as the worst (or equal worst) and cigarette 506 as the best (or equal best). Similarly, the overall ranking resulting from all 500 fabrics also agrees with the ranking of the cotton ducks. Table 6 includes additional detail, by showing that 60% of the fabrics classify cigarette 506 as the best (least ignition-prone) and cigarettes 519, 525 and 528 as the three worst, and almost 70% classify cigarette 506 as one of the two best. On the other hand, only 5% classify cigarette 506 as the worst (most ignition-prone), 9% as one of the two worst and 6% classify cigarettes 506 and 508 as the worst 2. The comments made here are illustrated in Fig. 1. The 'cotton ducks' rank the five cigarettes used as follows, in order of increasing ignition propensity:

$$506 < 508 < 528 = 525 = 519$$

The analysis indicates that only 13 of the 145 fabrics are severely misrepresented by the 'cotton ducks' (i.e. approximately 8% of the total) when they classify cigarettes #506 and #508 as significantly better than the other three cigarettes. Moreover, an analysis that were to

Table 5. Ignition propensity results for the various cigarettes (Results in % Ignitions)

Cigarette #	519	506	508	525	528	Avg
Cotton ducks	100	14	35	100	100	70
NIST Like-1	87	24	46	87	83	66
NIST Like-2	90	21	56	76	71	64
NIST Unlike	65	38	60	49	37	50
Others	74	53	60	64	62	63
Overall	76	43	57	67	63	61
Ranking for ducks	3	1	2	3	3	
Ranking for NIST Like-1	3–4	1	2	3–4	3–4	
Ranking for NIST Like-2	5	1	2	4	3	
Ranking for NIST Unlike	5	1–2	4	3	1–2	
Ranking for others	5	1	2	3–4	3–4	
Ranking overall	5	1	2	4	3	

Table 6. How the 500 fabrics classify cigarettes (results in # of fabrics)

	NIST Like-1	NIST Like-2	NIST Unlike	Others	All	% of All
All 100% igniton	0	1	1	28	30	21
506 best	20	12	11	46	88	61
506 among best 2	21	13	16	51	99	68
506 worst	0	0	1	6	7	5
506 among worst 2	0	0	6	7	13	9
519, 525, 528 worst 3	20	12	9	43	84	58
506, 508 worst 2	0	0	4	4	8	6
None of the above	1	0	1	2	4	3

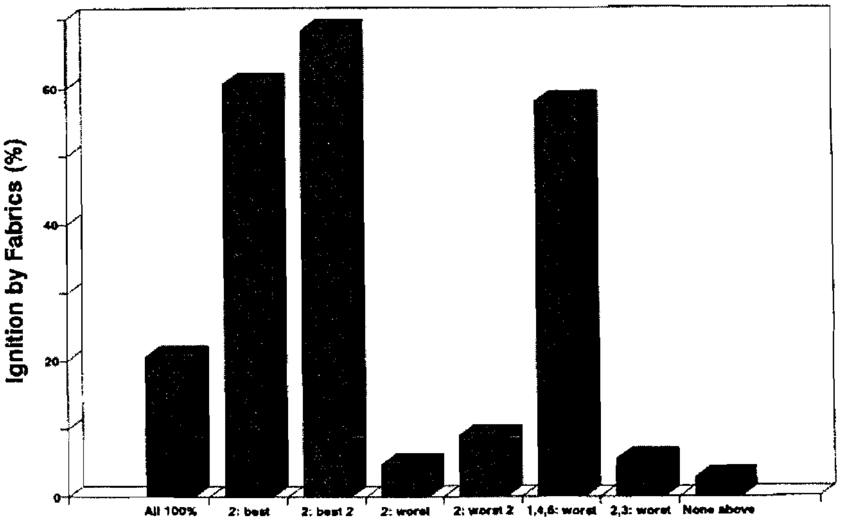

Figure 1. Ignition propensity test results of the 145 ignitable fabrics, within the 500 fabric study: % of fabrics for which: all ignite 100%; cigarette 2 (506) is one of the best two; cigarette 2 (506) is the best; cigarette 2 (506) is the worst; cigarette 2 (506) is one of the worst two; cigarettes 1, 4, 5 (519, 525, 528) are the worst three; cigarettes 2, 3 (506, 508) are the worst two; and 'none of the above'.

classify the other cigarettes as the better one would misrepresent 99 of the 145 fabrics (68% of the total) which classify cigarettes #528, #525 and #519 as having the most propensity to ignite fabrics (or at least not better than cigarettes #506 and #508).

However, it must be remembered that there are many fabrics that are not ignitable by any cigarette (particularly those with low cellulosic content, or even nonfully cellulosic) and there are a number of fabrics for which there is little difference in ignitability of many

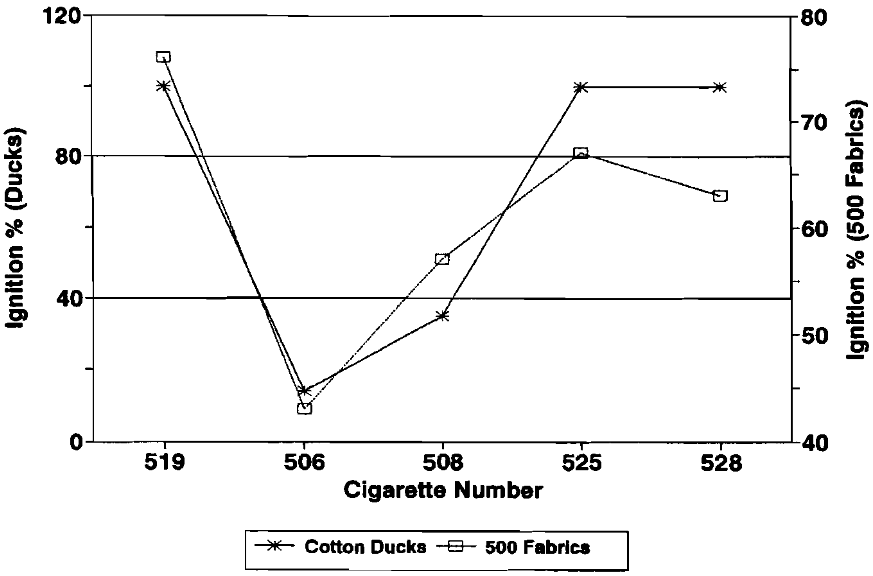

Figure 2. Comparison of ignition propensity test results with the cotton ducks (NIST 851 test) and with the 500 upholstery fabrics.

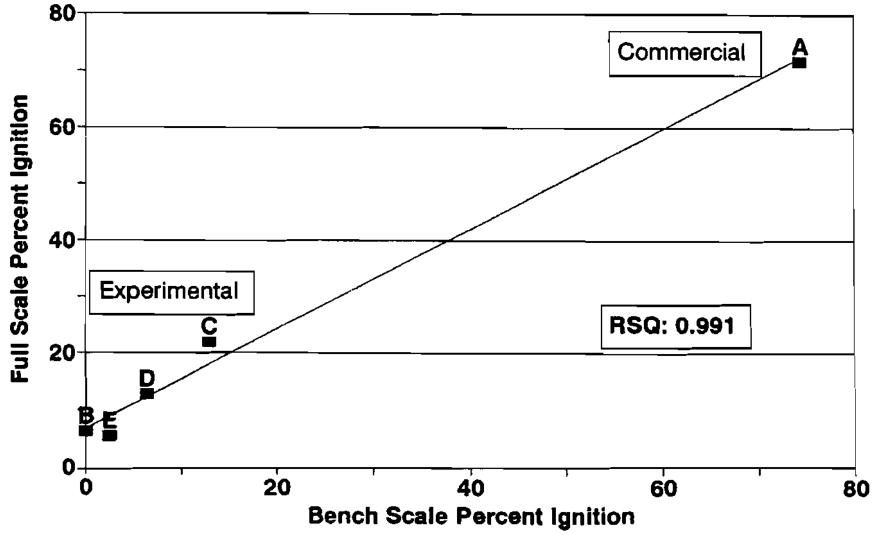

Figure 3. Correlation between bench-scale test results and full-scale test results for five cigarettes (TSG work): A is a commercial cigarette and the others are experimental.

cigarettes. However, when those fabrics are considered for which the characteristics of the cigarette can affect their ignitability, the NIST 851 test predicts the probability of ignition for the majority of them. This is exemplified in Fig. 2. This figure displays the ignition propensity of the five cigarettes tested using the cotton ducks (NIST 851 test) and using the overall summary of the 500 fabrics. The consistency of the pattern is clearly very adequate.

In summary, this study indicates that, as was to be expected, not all fabrics behave alike in terms of their ignitability when confronted by cigarettes, but that, on balance, the 500 fabrics give results consistent with those given by the cotton ducks chosen for the NIST 851 mock-up test, with only less than 10% of fabrics producing very different results. This validates the choice of the cotton ducks as substrates, and shows that the NIST 851 'cotton duck' test can be validly used to assess ignition propensity of cigarettes.

ADDITIONAL ANALYSIS

Figure 3 shows a comparison between the results of the original NIST/TSG test for cigarette ignition[14] with those of full-scale tests for smoldering ignition of upholstered furniture, in two ways. It contains a comparison of overall results per cigarette: a commercial cigarette (A) and four experimental cigarettes (B, C, D and E) were tested, and a correlation coefficient of 0.991 was obtained. It is also clear from the figure that the commercial cigarette has an ignition propensity of approximately 70%, while the experimental cigarettes have ignition propensities of less than 30%.

Figure 4 includes a somewhat different analysis of the difference in ignition propensity of the various cigarettes. In the testing 18 fabric/foam combinations were used in the full-scale tests and 15 combinations in the small-scale test: a total of 33 fabric combinations. The analysis shows that almost all fabric systems correctly predict that cigarette B is the best or one of the two or three best, and that the commercial cigarette is the worst or one of the two worst. On the other hand, no system predicts that cigarettes B, D and E are the three worst, and only five of 33 systems predict that cigarette B is the worst.

As an added note, Fig. 5 includes a comparison of the results on cigarette ignition propensity of five cigarettes using: (a) the TSG test described above [14], (b) the

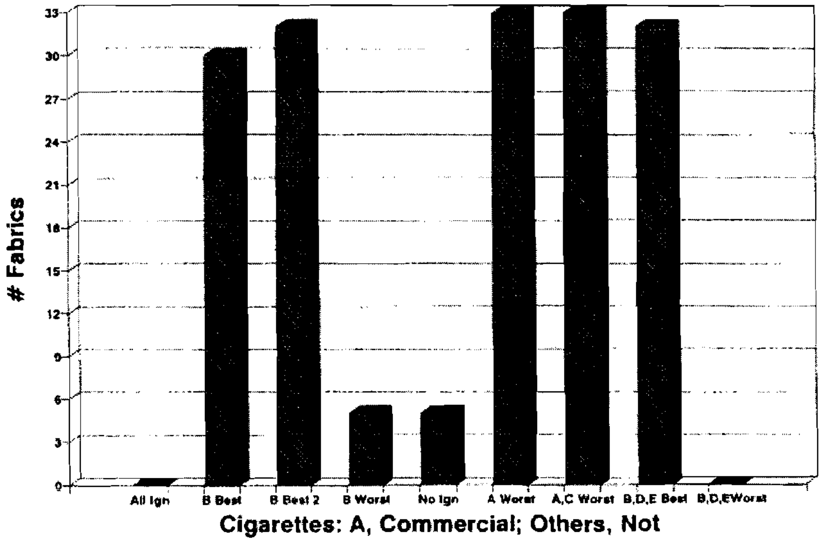

Figure 4. Discrimination between cigarettes by the TSG small-scale and full-scale studies, with 33 fabric systems: 18 full-scale and 15 bench-scale ones. # of fabrics for which: all ignite 100%; cigarette B is the best; cigarette B is one of the best two; cigarette B is the worst; none of the cigarettes cause ignitions; cigarette A is the worst; cigarettes A and C are the worst two; cigarettes B, D, E are the worst three; cigarettes B, D, E are the best three; and cigarettes B, D, E are the worst three.

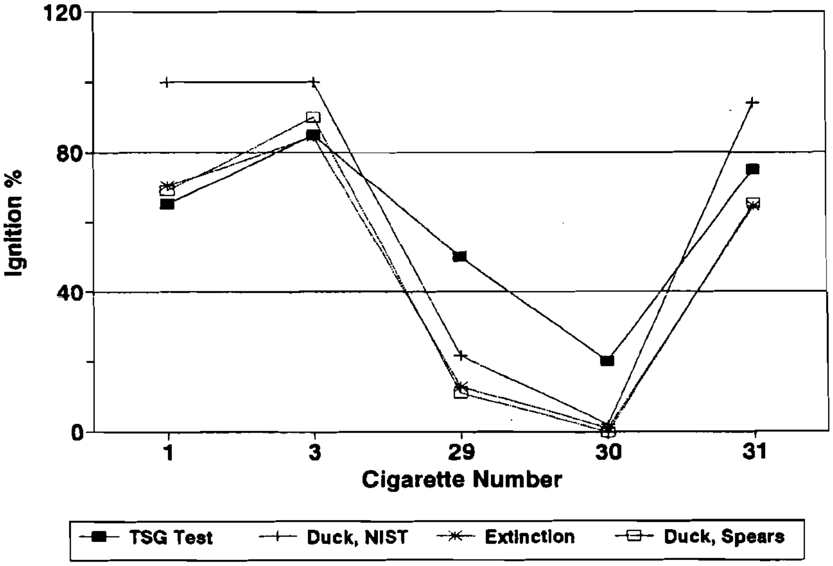

Figure 5. Comparison of four test methods on cigarette ignition propensity: (a) the TSG test described; (b) the 'cotton duck' test, as described in NIST 851, and tested by NIST; (c) a surrogate extinction test as conducted by NIST and (d) the 'cotton duck' test, as described in NIST 851, and conducted by Spears, using newer versions of the same types of cigarettes.

'cotton duck' test as used by NIST,[10] (c) a surrogate extinction test, proposed by the TAG and as conducted by NIST[10] and (d) the 'cotton duck' test as conducted by Spears,[21,23] using newer versions of the same types of cigarettes. The similarity of results is very interesting. A caveat is needed: the TSG test results were conducted with the '100 series' cigarettes, which are not identical to the '500 series' cigarettes, but show similar trends.

COMPARISON OF FLAMING AND SMOLDERING IGNITION

There were 320 purely cellulosic fabrics in this study, of which 121 were ignitable. Figure 6 shows (a) the average percentage of ignitions recorded for the cellulosic fabrics for various density ranges and (b) the percentage of fabrics that are ignitable in the corresponding density

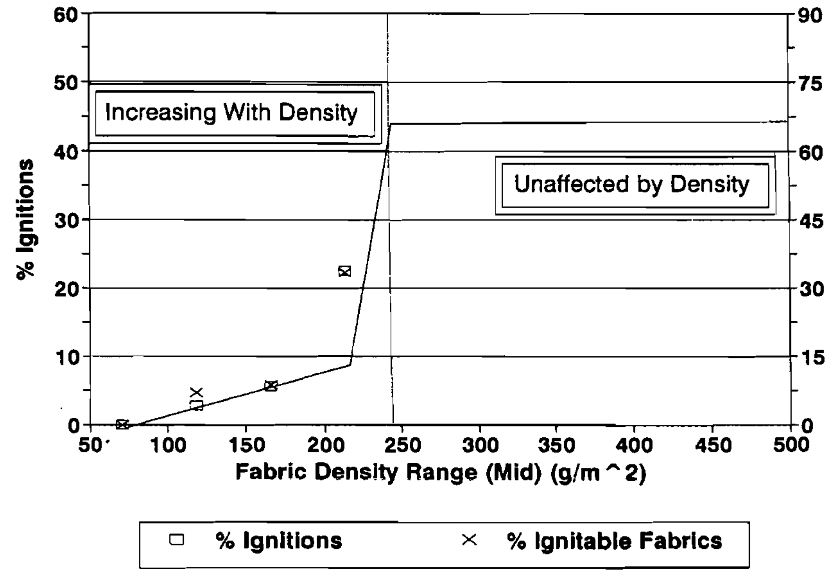

Figure 6. Percentage of ignitions obtained with purely cellulosic fabrics and percentage of purely cellulosic fabrics which are ignitable, as a function of the fabric density range (data represent the middle of the range in each case).

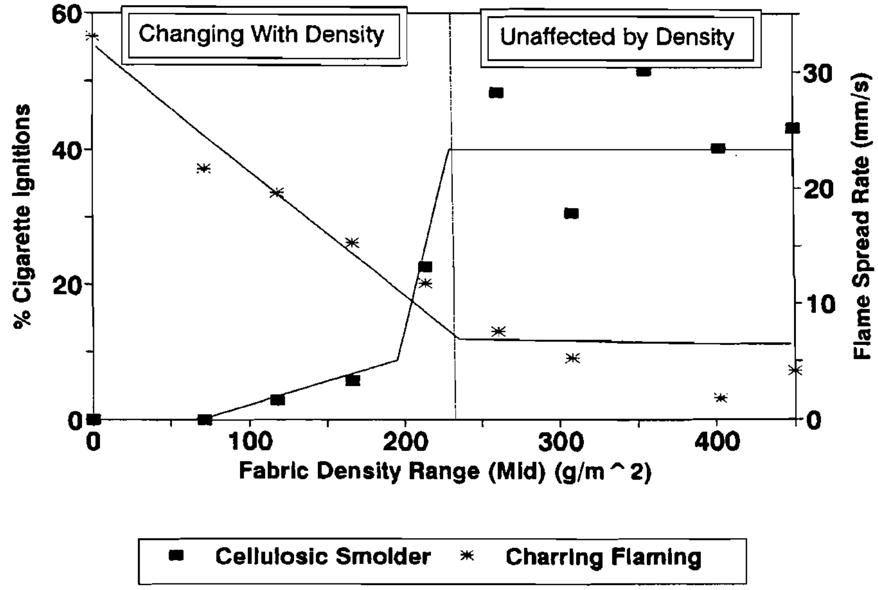

Figure 7. Comparison of the thresholds for constant probability of cellulosic smoldering ignition and charring flame spread rate, based on fabric density.

range, where each density range covers 2 oz yd^{-2} (or almost 50 g m^{-2}). It appears from the figure that the density of the cellulosic fabric actually has little effect on the ignitability of the fabric if the density exceeds a value of 200–250 g m^{-2} (8–10 oz yd^{-2}). On the other hand, both the probability of ignition and the fraction of ignitable fabrics increases with density if the fabric density is less than that threshold. Since all the cotton duck fabrics and most upholstery fabrics tend to have densities above the threshold (58% of all purely cellulosic fabrics and 64% of all fabrics in this study have densities over 200 g m^{-2} (or 8 oz yd^{-2})), this suggests that the weight of the cotton ducks has little effect on the ignitability of the fabric by cigarettes. It is also worth noting that the threshold obtained for smoldering ignition of cellulosic fabrics in this study is almost the same as the threshold found for flame spread rate following flaming ignition of charring fabrics in a different study.[24] However, the flame spread rate of the charring fabrics, which was also unaffected by fabric density above approximately 200 g m^{-2} (8–9 oz yd^{-2}), decreased with increasing fabric density below that value (Fig. 7). This (1) indicates the divergent effects that can be found for different types of ignition sources and (2) suggests that fabric density is most important in terms of flammability at low fabric densities.

CONCLUSIONS

The results of two studies of cigarette ignition propensity were compared: (1) using a selection of 500 upholstery fabrics, representative of those available in the US market in the early 1990s and (2) using three 'cotton ducks', which have very different properties from traditional upholstery fabrics. The results of the analysis indicate that the 'cotton ducks' are an adequate overall representation of the relative ignition propensity of the cigarettes, as assessed by typical upholstery fabrics. Moreover, the test method that uses the 'cotton ducks' appears to give results which correlate well with those of full-scale upholstered furniture smoldering ignition fire tests. Thus, the test method using 'cotton ducks' is an adequate representation of the ignition propensity of cigarettes on the vast majority of commercial upholstery fabrics.

APPENDIX A: PHYSICAL PROPERTIES OF 500 FABRICS CHOSEN

Fabric #	Potassium ppm	Sodium ppm	Sodium + potassium ppm	Porosity Coresta units	Density oz yd^{-2}	Cotton %	Cellulose %
1	136.0	1 603.0	1739	3825	17.87	91	100
2	24.5	464.5	489	11 229	8.92	100	100
3	105.6	304.5	410	8 598	12.73	37	37
4	16.0	1 715.0	1731	5 000	11.81	100	100
5	18.2	373.5	392	6 404	13.84	33	100
6	106.4	1 407.0	1513	10 959	13.56	100	100
7	85.0	974.0	1059	4 688	16.87	91	100
8	203.3	401.0	604	2 008	16.91	71	71
9	2 051.0	450.0	2501	3 170	11.45	24	100
10	44.8	538.2	583	11 470	13.25	100	100
11	219.0	1 143.0	1362	9 171	16.46	81	81
12	226.0	1 816.0	2042	9 692	15.97	100	100
13	1 658.0	592.0	2250	9 205	10.03	100	100
14	1 130.0	898.0	2028	5 418	14.46	90	90
15	248.0	2 523.0	2771	6 454	19.43	94	94
16	90.3	466.0	556	2 980	7.49	0	46
17	25.9	359.0	385	3 314	19.68	100	100
18	471.2	311.5	783	12 511	11.73	40	100
19	59.0	1 637.0	1696	9 391	15.64	100	100
20	37.6	517.2	555	9 340	9.80	100	100
21	43.1	619.3	662	6 926	13.43	78	78
22	302.8	1 013.0	1316	11 204	17.52	24	100
23	54.8	774.0	829	5 145	11.90	68	100
24	43.0	1 790.0	1833	9 633	18.12	100	100
25	434.9	954.2	1389	11 308	14.26	61	61
26	190.2	2 308.0	2498	6 986	13.80	100	100
27	84.1	1 288.0	1372	12 480	12.71	72	72
28	39.7	730.9	771	3 615	16.00	81	100
29	97.3	952.6	1050	6 697	17.48	75	75
30	196.7	979.5	1176	7 114	14.33	69	69
31	47.0	1 147.0	1194	7 327	10.41	100	100
32	45.0	1661.0	1 706	8 423	14.96	39	100
33	93.4	11 512.0	11 605	5 711	11.24	100	100
34	554.0	482.0	1 036	2 657	16.70	84	100
35	43.7	750.7	794	8 187	15.76	63	63
36	244.6	1 100.0	1 345	8 634	14.79	64	64
37	26.0	1 697.0	1 723	2 815	15.55	100	100
38	36.3	3 127.0	3 163	7 204	14.14	100	100
39	78.4	1 182.0	1 260	5 022	10.82	100	100
40	125.0	1 750.0	1 875	4 649	16.46	100	100
41	39.3	437.2	477	6 048	9.33	57	57

APPENDIX A. CONTINUED

Fabric #	Potassium ppm	Sodium ppm	Sodium + potassium ppm	Porosity Coresta units	Density oz yd $^{-2}$	Cotton %	Cellulose %
42	999.0	1 197.0	2 196	1 208	16.95	100	100
43	543.0	929.7	1 473	6 573	13.25	76	76
44	28.0	736.0	764	6 844	12.43	100	100
45	1 103.0	1 567.0	2 670	6 651	10.17	100	100
46	1 408.0	1 600.0	3 008	4 849	16.26	100	100
47	1 175.0	834.0	2 009	4 647	9.46	100	100
48	439.2	919.5	1 359	5 711	14.02	62	62
49	43.0	1 168.0	1 211	8 010	12.52	100	100
50	161.9	434.0	596	6 058	14.77	31	100
51	104.0	1 726.0	1 830	6 895	12.14	85	85
52	58.0	811.0	869	13 618	15.93	81	81
53	29.7	1004.0	1 034	13 800	11.03	100	100
54	69.0	1 426.0	1 495	5 872	11.83	100	100
55	2 044.0	1 200.0	3 244	3 360	9.30	100	100
56	142.0	2 148.0	2 290	15 002	9.22	100	100
57	470.4	1 026.0	1 496	8 974	18.96	100	100
58	16.9	2 304.0	2 321	6 798	13.00	100	100
59	1 877.0	654.8	2 532	4 262	10.13	100	100
60	43.2	1 847.0	1 890	6 308	13.02	100	100
61	249.0	2 498.0	2 747	10 682	7.40	100	100
62	1 403.0	739.0	2 142	10 692	10.74	100	100
63	32.9	1 039.0	1 072	4 017	15.72	70	70
64	47.9	1 900.0	1 948	9 937	10.50	100	100
65	475.0	1 619.0	2 094	8 397	14.29	80	100
66	89.0	3 123.0	3 212	5 036	16.78	29	100
67	158.0	1 800.0	1 958	5 016	16.48	100	100
68	17.0	1 857.0	1 874	5 316	15.67	100	100
69	54.6	1 032.0	1 087	8 852	16.94	59	59
70	32.0	1 938.0	1 970	5 346	18.07	100	100
71	1 512.0	1 151.0	2 663	11 515	11.63	100	100
72	3 598.0	775.0	4 373	5 282	8.95	100	100
73	640.1	1 407.0	2 047	9 261	12.56	40	100
74	738.0	1 143.0	1 881	6 704	17.62	100	100
75	104.1	1 328.0	1 432	11 199	17.35	100	100
76	1 400.0	1 138.0	2 538	2 756	11.98	100	100
77	500.0	366.0	866	12 638	12.20	38	100
78	1 368.0	902.0	2 270	6 082	14.86	100	100
79	2 515.0	982.0	3 497	4 930	10.61	100	100
80	30.8	647.5	678	5 681	17.21	100	100
81	45.5	2 419.0	2 465	4 968	15.74	72	72
82	58.2	403.8	462	6 074	8.81	100	100
83	2 091.0	880.0	2 971	3 474	11.90	100	100
84	1 991.0	828.0	2 819	5 851	10.46	100	100
85	1 781.0	782.0	2 563	7 299	10.62	100	100
86	946.0	1221.0	2 167	5 128	15.60	50	100
87	1 221.0	2 217.0	3 438	2 019	15.89	65	100
88	2 737.0	884.0	3 621	7 420	10.27	100	100
89	85.7	1 272.0	1 358	10 505	12.97	46	200
90	2 865.0	782.0	3 647	6 604	10.49	100	100
91	1 717.0	1 096.0	2 813	4 971	10.91	100	100
92	794.9	939.8	1 735	7 361	16.04	78	78
93	38.5	411.2	450	6 200	8.33	39	39
94	42.5	304.2	347	5 660	9.96	0	0
95	71.5	157.3	229	2 944	11.68	40	100
96	63.7	569.6	633	1 049	8.04	0	75
97	1 545.0	925.6	2 471	4 496	10.56	100	100
98	42.0	940.7	983	6 120	9.86	100	100
99	32.3	122.4	155	10 761	10.91	100	100
100	2 903.0	467.0	3 370	7 804	9.90	100	100
101	78.1	1 510.0	1 588	8 851	9.75	61	100
102	72.5	1 122.0	1 195	7 182	15.07	15	100
103	29.0	2 821.0	2 850	12 972	14.63	100	100
104	26.2	1 363.0	1 389	8 076	8.28	77	77
105	1 534.0	957.0	2 491	5 745	6.67	100	100
106	1 671.0	977.0	2 648	7 745	10.17	100	100
107	64.0	1 589.0	1 653	6 571	15.49	100	100
108	48.0	2 958.0	3 006	5 800	15.29	100	100
109	44.8	836.0	881	11 970	6.90	100	100
110	106.0	1 975.0	2 081	4 059	4.56	100	100
111	45.2	812.9	858	14 902	13.26	71	71
112	12.7	1 751.0	1 764	11 130	14.26	71	71
113	1 371.0	1 295.0	2 666	1 859	13.38	100	100
114	341.0	219.6	561	4 577	9.84	93	93

APPENDIX A. CONTINUED

Fabric #	Potassium ppm	Sodium ppm	Sodium + potassium ppm	Porosity Coresta units	Density oz yd^{-2}	Cotton %	Cellulose %
115	37.7	1 264.0	1 302	2 915	15.57	100	100
116	78.3	1 177.0	1 255	2 966	13.63	100	100
117	45.1	280.5	326	10 290	9.26	50	50
118	41.7	4 197.0	4 239	2 451	12.53	100	100
119	45.0	3 290.0	3 335	8 957	12.23	76	100
120	49.0	3 468.0	3 517	4 011	16.00	100	100
121	75.0	2 769.0	2 844	7 641	16.40	85	85
122	582.0	3238.0	3 238	3 232	19.46	100	100
123	12.2	1 223.0	1 235	6 041	15.48	43	100
124	38.3	722.6	761	4	11.63	100	100
125	291.8	340.3	632	7 178	7.06	70	100
126	166.6	700.6	867	2 557	12.33	100	100
127	1 547.0	657.0	2 204	10 146	12.99	100	100
128	6.7	1045.0	1 052	3 878	15.31	82	82
129	0.0	3 107.0	3 107	2 739	16.47	100	100
130	49.3	1 205.0	1 254	10 410	16.60	29	65
131	136.0	1 867.0	2 003	3 948	15.54	100	100
132	114.5	499.7	614	5 676	11.15	100	100
133	13.5	294.1	308	6 391	13.83	51	69
134	5.2	1 129.0	1 134	6 793	9.53	100	100
135	1 043.0	611.0	1 654	3 944	13.52	5	100
136	23.6	2 759.0	2 783	7 605	10.66	100	100
137	84.6	449.7	534	4 860	8.21	100	100
138	33.7	1 917.0	1 951	9 413	19.92	85	85
139	3.1	1 423.0	1 426	8 821	15.34	29	65
140	54.0	2 496.0	2 550	2 727	19.34	91	100
141	71.0	2 570.0	2 641	8 950	23.98	76	76
142	39.9	892.0	932	7 473	13.74	100	100
143	17.3	1 619.0	1 636	7 528	11.00	100	100
144	116.1	575.8	692	4 353	7.75	0	0
145	2 183.0	1 430.0	3 613	6 746	10.63	100	100
146	86.0	1 707.0	1 793	6 761	16.48	100	100
147	3.0	1 736.0	1 739	5 584	19.08	100	100
148	1 643.0	1 272.0	2 915	4 638	14.45	100	100
149	8.5	1 393.0	1 402	8 800	11.67	0	77
150	22.0	2 272.0	2 294	8 739	14.67	39	100
151	21.0	2 091.0	2 112	1 875	15.06	100	100
152	26.8	1 224.0	1 251	6 734	10.62	0	100
153	43.1	1 254.0	1 297	4 541	8.72	0	100
154	21.0	608.0	629	3 338	9.36	51	100
155	665.0	2 137.0	2 802	5 082	14.73	49	100
156	31.0	1 557.0	1 588	6 208	8.27	57	57
157	25.5	1 041.0	1 066.5	6 661	17.35	100	100
158	27.8	843.2	871	13 190	7.87	100	100
159	21.0	1 165.0	1 186	8 946	14.93	64	64
160	35.1	1 172.0	1 207	12 614	8.14	64	64
161	37.7	1 322.0	1 360	9 306	7.14	100	100
162	2 795.0	617.0	3 412	7 038	9.96	100	100
163	238.8	355.6	594	4 848	6.51	71	71
164	1 019.0	764.0	1 783	7 077	15.17	96	96
165	1 057.0	847.3	1 904	6 186	10.35	10	10
166	87.5	1 110.0	1 198	5 665	11.10	100	100
167	19.6	606.0	626	12 717	5.77	100	100
168	20.4	1 299.0	1 319	4 872	7.52	100	100
169	102.0	2 005.0	2 107	3 007	12.83	0	100
170	57.6	279.8	337	6 082	3.46	50	50
171	17.8	194.0	212	2 907	6.60	100	100
172	34.5	254.2	289	7 726	4.18	100	100
173	36.8	195.0	232	3 408	6.73	100	100
174	37.6	157.9	196	14 914	5.67	100	100
175	205.9	480.4	686	3 874	6.33	100	100
176	32.2	148.6	181	4 762	6.42	35	35
177	26.8	183.2	210	11 828	5.56	100	100
178	659.0	600.0	1 259	5 912	6.30	100	100
179	30.2	354.6	385	4 085	6.80	100	100
180	105.0	262.3	367	13 966	6.10	100	100
181	60.4	331.6	392	10 525	5.91	100	100
182	57.7	460.6	518	8 970	6.16	100	100
183	431.7	532.5	964	6 987	6.35	100	100
184	130.7	410.2	541	6 238	6.78	100	100
185	276.7	486.2	763	7 940	6.13	100	100
186	80.8	303.2	384	14 108	3.15	100	100
187	32.3	57.5	90	3 253	6.23	100	100

APPENDIX A. CONTINUED

Fabric #	Potassium ppm	Sodium ppm	Sodium + potassium ppm	Porosity Coresta units	Density oz yd^{-2}	Cotton %	Cellulose %
188	41.5	258.9	300	4 347	6.29	0	65
189	18.4	361.9	380	8 351	6.03	100	100
190	8.0	106.5	115	7 612	3.44	100	100
191	27.4	79.6	107	1 115	4.82	100	100
192	52.5	462.6	515	4 654	3.61	50	50
193	49.1	222.6	272	4 524	4.02	100	100
194	4.5	70.1	75	4 480	6.49	100	100
195	29.9	55.5	85	11 534	7.91	49.4	49.4
196	31.9	346.8	379	2 052	4.75	100	100
197	22.4	381.4	404	4 588	6.12	100	100
198	10.4	222.3	233	6 211	6.68	100	100
199	10.0	146.0	156	5 421	4.63	100	100
200	31.4	132.2	164	12 780	3.95	100	100
201	13.9	409.0	423	4 392	7.81	100	100
202	24.8	23.2	48	3 993	5.71	100	100
203	156.8	492.0	649	2 406	4.51	100	100
204	38.0	120.8	159	2 750	4.40	100	100
205	39.0	329.4	368	3 793	4.54	100	100
206	6.9	359.9	367	4 601	6.29	100	100
207	117.5	411.3	529	7 202	6.75	100	100
208	3.4	554.0	557	3 522	6.61	100	100
209	15.3	400.2	416	4 798	5.27	100	100
210	27.4	261.1	289	1 349	5.06	100	100
211	93.8	247.1	341	14 118	4.94	100	100
212	32.8	85.2	118	5 291	5.02	100	100
213	36.8	55.3	92	3 015	6.11	100	100
214	51.1	167.8	219	1 746	5.09	100	100
215	222.8	968.3	1191	9 573	6.40	100	100
216	14.0	336.7	351	3 284	6.09	100	100
217	43.0	127.8	171	2 335	6.06	100	100
218	77.3	432.6	510	7 079	3.47	50	50
219	69.2	387.9	457	1 517	6.19	100	100
220	32.9	989.1	1 022	2 648	7.25	100	100
221	147.3	413.9	561	2 692	7.44	70	70
222	44.9	230.1	275	3 179	4.10	100	100
223	25.3	226.4	252	4 569	5.97	100	100
224	37.0	209.9	247	3 293	5.77	100	100
225	98.2	771.6	870	9 501	6.40	100	100
226	20.1	387.7	408	2 104	6.82	100	100
227	43.7	1032.0	1 076	20 993	4.90	56	56
228	31.5	228.4	260	2 774	6.35	100	100
229	72.4	549.4	622	2 955	4.86	100	100
230	23.4	178.8	202	5 714	4.75	100	100
231	1 784.0	1 209.0	2 993	7 956	4.02	100	100
232	22.0	474.0	496	4 196	8.16	100	100
233	56.8	858.4	915	11 163	8.29	100	100
234	32.0	1 161.0	1 193	6329	15.02	100	100
235	28.2	835.6	864	7 420	8.02	49	51
236	15.4	985.0	1 000	3 873	8.94	0	100
237	54.1	1 036.0	1 090	2 092	10.36	0	69
238	24.0	4 404.0	4 428	3 535	8.78	100	100
239	66.0	86.7	153	7 239	9.39	54	46
240	94.5	641.4	736	6 994	9.83	60	60
241	34.9	669.6	705	4 372	6.84	0	75
242	12.3	607.0	619	8 477	8.11	100	100
243	29.9	412.0	442	5 391	10.30	40	100
244	85.3	772.3	858	11 490	7.54	55	55
245	735.8	2 777.0	3 513	6 655	17.07	48	87
246	88.0	3 662.0	3 750	9 486	13.82	75	75
247	43.0	2 347.0	2 390	8 202	8.29	0	100
248	29.1	1 127.0	1 156	11 514	10.05	2	66
249	71.0	309.5	381	11 866	12.72	73	73
250	15.0	2 154.0	2 169	11 393	13.25	10	96
251	17.0	1 078.0	1 095	9 128	13.24	0	76
252	976.0	959.0	1935	11 748	9.94	30	30
253	60.2	339.8	400	7 846	11.95	10	96
254	19.7	988.8	1 009	12 604	12.94	0	76
255	21.9	1 008.0	1 030	3 855	14.11	30	30
256	96.0	3 290.0	3 386	5 409	16.50	96	96
257	84.1	869.4	954	5 521	15.70	0	72
258	390.8	323.4	714	6 270	11.30	100	100
259	181.5	1 053.0	1 235	7 860	11.88	26	100
260	26.0	1 155.0	1 181	3 989	9.40	33	33

APPENDIX A. CONTINUED

Fabric #	Potassium ppm	Sodium ppm	Sodium + potassium ppm	Porosity Coresta units	Density oz yd^{-2}	Cotton %	Cellulose %
261	23.4	166.1	190	9 227	16.89	100	100
262	92.0	2 099.0	2 191	3 314	15.01	46	100
263	671.4	934.5	1 606	3 447	13.97	17	75
264	28.0	1 688.0	1 716	4 178	15.06	36	100
265	67.2	999.2	1 066	7 254	9.85	100	100
266	29.7	1 008.0	1 038	5 819	9.41	0	100
267	19.1	209.9	229	0	12.55	100	100
268	29.1	779.2	808	5 332	12.73	41	80
269	23.2	382.1	405	3 646	8.47	100	100
270	10.5	423.8	434	10 042	8.93	100	100
271	20.3	970.6	991	7 644	7.49	100	100
272	15.8	199.3	215	2 182	9.36	60	60
273	31.1	987.7	1 019	11 226	8.56	100	100
274	5.8	168.5	174	4 373	7.84	100	100
275	113.0	163.4	276	6 910	6.75	51	51
276	58.0	2 193.0	2 251	5 007	10.04	49	49
277	38.2	287.0	325	10 318	8.48	100	100
278	23.3	460.6	484	4 879	12.39	0	0
279	10.1	1 140.0	1 150	10 972	12.77	0	73
280	11.5	217.5	229	7 183	19.19	45	45
281	0.0	269.0	269	1 573	4.53	100	100
282	316.4	1 175.0	1 491	3 618	10.99	74	74
283	25.9	3 399.0	3 425	2 601	15.76	55	100
284	18.7	466.7	485	3 535	10.49	100	100
285	651.7	404.7	1 056	11 732	14.53	0	0
286	81.0	1 732.0	1 813	4 384	11.14	0	100
287	42.0	1 260.0	1 302	6 586	12.72	0	100
288	10.1	889.1	899	10 458	6.78	49	49
289	41.0	1 755.0	1 796	4 341	10.01	77	100
290	32.6	1 074.0	1 107	6 085	9.94	46	100
291	32.2	223.2	255	3 991	6.49	0	0
292	27.4	664.7	692	13 242	6.78	50	50
293	9.8	1 761.0	1 771	6 655	11.89	100	100
294	7.2	932.6	940	9 335	5.57	35	100
295	4 989.0	325.0	5 314	8 936	13.30	65	100
296	19.8	263.4	283	7 438	9.87	42	100
297	30.1	71.1	101	13 058	14.05	80	80
298	60.9	106.0	167	8 437	10.75	78	78
299	2 944.0	467.0	3 411	5 517	12.37	66	66
300	88.0	2 490.0	2 578	9 761	6.94	100	100
301	1 700.0	1 213.0	2 913	6 851	10.62	100	100
302	114.0	1 564.0	1 678	4 576	17.38	31	100
303	56.3	1 173.0	1 229	4 766	9.27	25	60
304	2 836.0	597.0	3 433	4 571	10.33	59	100
305	32.3	727.6	760	9 421	9.22	100	100
306	15.6	153.4	169	1 768	11.72	100	100
307	61.5	227.6	289	3 771	4.73	100	100
308	27.6	3 902.0	3930	2 535	6.62	100	100
309	21.1	422.4	444	8 394	16.37	28	64
310	55.6	1 073.0	1 129	2 404	6.30	100	100
311	85.5	226.0	312	5 050	4.53	100	100
312	42.2	246.1	288	3 243	4.58	100	100
313	43.7	277.6	321	2 531	6.54	100	100
314	101.7	1 565.0	1 667	9 439	11.94	100	100
315	17.3	148.8	166	7 996	6.86	100	100
316	49.0	265.4	314	2 032	4.70	100	100
317	55.8	116.7	173	8 947	7.21	100	100
318	26.9	122.8	150	12 295	4.88	100	100
319	42.9	994.0	1 037	9 728	7.28	100	100
320	14.3	209.2	224	5 927	6.89	100	100
321	27.6	204.8	232	1 481	4.95	100	100
322	59.6	143.0	203	6 312	7.02	100	100
323	45.5	114.8	160	9 832	7.03	100	100
324	14.7	507.8	523	2 585	4.91	100	100
325	27.5	374.4	402	3 810	5.55	100	100
326	9.9	91.0	101	5 348	7.65	100	100
327	18.3	142.1	160	4 665	4.86	100	100
328	14.6	128.0	143	5 845	6.35	100	100
329	44.1	98.9	143	9 685	6.52	100	100
330	764.2	2 353.0	3 117	2 093	5.36	100	100
331	25.4	46.3	72	6 780	4.50	100	100
332	36.5	434.9	471	1 959	4.34	100	100
333	13.8	232.9	247	10 010	6.97	100	100

APPENDIX A. CONTINUED

Fabric #	Potassium ppm	Sodium ppm	Sodium + potassium ppm	Porosity Coresta units	Density oz yd $^{-2}$	Cotton %	Cellulose %
334	17.9	116.7	135	2 369	4.62	100	100
335	44.0	178.6	223	7 592	7.08	100	100
336	26.0	157.3	183	6 380	4.58	100	100
337	46.9	220.7	268	5 270	7.64	100	100
338	29.8	217.6	247	3 356	5.93	100	100
339	16.3	59.8	76	9 326	6.36	100	100
340	56.0	106.4	162	11 552	6.91	100	100
341	2 359.0	171.0	2 530	8 815	7.10	100	100
342	17.5	73.5	91	1 702	6.32	100	100
343	13.8	76.5	90	1 324	2.78	0	0
344	35.3	61.4	97	5 592	6.56	33	33
345	29.3	454.5	484	1 632	4.87	100	100
346	51.9	427.9	480	17 763	5.73	100	100
347	32.2	410.1	442	6 647	7.52	100	100
348	41.3	139.4	181	11 144	4.48	58	58
349	70.4	3 888.0	3 958	4 139	8.86	100	100
350	0.0	207.0	207	925	4.89	100	100
351	62.9	398.0	461	2 424	7.24	100	100
352	61.7	361.2	423	8 134	12.04	0	0
353	61.5	432.0	494	6 385	6.01	100	100
354	42.4	147.2	190	15 883	3.34	100	100
355	60.0	101.1	161	10 035	7.72	100	100
356	43.6	593.0	637	4 847	8.70	100	100
357	75.7	355.3	431	6 894	4.72	100	100
358	26.4	397.1	424	2 498	8.09	100	100
359	18.1	293.5	312	5 575	8.16	100	100
360	18.7	99.7	118	9 215	6.74	100	100
361	18.6	467.9	487	4 623	3.96	0	18
362	40.1	457.0	497	4 746	4.10	0	21
363	1 340.0	416.1	1 756	1 827	15.27	100	100
364	16.0	322.3	338	13 566	12.69	19	19
365	18.7	381.1	400	5 681	9.22	66	66
366	39.0	410.0	449	5 454	16.59	100	100
367	25.7	384.4	410	5 604	10.63	100	100
368	12.3	388.6	401	5 713	7.36	100	100
369	41.7	372.4	414	9 410	8.90	60	60
370	23.9	380.6	405	6 762	10.47	100	100
371	12.8	390.6	403	8 463	10.16	100	100
372	13.7	388.1	402	2 708	7.14	70	70
373	13.5	380.4	394	12 100	10.51	68	68
374	17.5	409.5	427	3 908	9.15	100	100
375	14.3	396.8	411	3 866	9.95	100	100
376	17.4	329.2	347	16 580	9.58	50	50
377	87.2	292.7	380	8 407	3.29	0	0
378	31.5	166.9	198	10 544	5.40	100	100
379	21.0	861.9	883	944	4.73	100	100
380	551.0	956.6	1 508	6 645	13.12	72	72
381	24.1	384.4	409	5 315	7.39	100	100
382	290.8	271.5	562	9 523	6.47	100	100
383	32.1	374.5	407	1 232	5.13	100	100
384	31.0	157.4	188	4 172	5.70	100	100
385	13.1	220.7	234	6 556	9.58	100	100
386	8.6	125.6	134	2 900	4.77	100	100
387	14.1	934.6	949	7 409	7.40	100	100
388	21.7	319.6	341	15 866	12.42	19	19
389	17.7	1 943.0	1 961	4 728	11.19	100	100
390	43.9	849.3	893	3 269	13.72	100	100
391	80.0	1 106.0	1 186	7 668	7.42	100	100
392	15.4	330.1	346	9 344	7.70	100	100
393	17.0	681.8	699	13 444	8.84	100	100
394	1 080.0	793.0	1 873	7 765	10.45	100	100
395	32.8	796.8	830	7 484	9.48	100	100
396	15.4	64.9	80	10 957	13.52	0	0
397	67.8	261.9	330	4 314	9.06	100	100
398	60.8	733.8	795	10 478	12.06	60	60
399	31.0	1 176.0	1207	4 068	10.10	100	100
400	69.4	998.5	1 068	3 994	5.06	54	54
401	25.1	1 333.0	1 358	7 786	12.33	100	100
402	1 269.0	207.8	1 477	9 061	9.13	50	50
403	45.2	995.2	1 040	4 800	9.29	100	100
404	162.5	1 181.0	1 344	23 238	5.72	0	0
405	616.9	776.0	1 393	8 460	17.31	62	62
406	123.8	717.4	841	5 233	9.68	0	0

APPENDIX A. CONTINUED

Fabric #	Potassium ppm	Sodium ppm	Sodium + potassium ppm	Porosity Coresta units	Density oz yd $^{-2}$	Cotton %	Cellulose %
407	604.0	643.0	1 247	17 790	9.90	100	100
408	51.6	787.5	839	10 222	17.09	0	0
409	171.3	837.1	1 008	11 523	6.43	0	57
410	28.0	74.3	102	0	19.84	0	0
411	261.4	1 030.0	1 291	10 789	9.68	0	13
412	131.4	687.7	819	3 076	10.56	55	55
413	543.4	1 034.0	1 577	983	14.33	25	25
414	54.8	656.0	711	4 613	10.81	100	100
415	123.1	891.4	1 015	2 968	12.33	7	7
416	105.4	51.0	156	3 828	6.77	0	0
417	71.7	183.1	255	10 432	15.89	0	0
418	103.5	1 005.5	1 109	9 262	9.47	100	100
419	3 130	765.0	3 895	5 416	20.23	67	67
420	4 220.0	397.8	4 618	3 705	12.91	100	100
421	95.2	813.6	909	12 060	6.78	26	26
422	2 557.0	494.7	3 052	5 340	9.90	83	83
423	62.1	945.5	1 008	4 068	10.30	64	64
424	116.3	463.6	580	11 191	14.57	96	96
425	201.1	1 143.0	1 344	11 820	6.64	0	0
426	22.4	3 798.0	3 820	5 903	5.42	100	100
427	363.1	600.7	964	2 160	10.64	79	79
428	65.0	477.5	543	9 134	9.17	62	62
429	2 826.0	1 035.0	3 861	7 069	11.95	100	100
430	221.1	809.7	1 031	6 853	11.95	83	83
431	240.9	778.7	1 020	14 178	11.57	0	0
432	146.0	589.0	735	7 280	5.87	100	100
433	88.9	5 244.0	5 333	2 524	6.92	50	50
434	116.6	548.6	665	5 051	5.90	100	100
435	104.1	1 006.0	1 110	7 157	7.17	53	53
436	124.6	936.6	1 061	7 839	9.21	100	100
437	899.1	233.0	1 132	8 804	11.02	55	55
438	115.6	411.8	527	10 689	13.58	67	67
439	33.8	301.0	335	6 967	16.30	100	100
440	51.1	404.2	455	7 593	12.18	43	43
441	97.9	399.0	497	8 650	6.47	45	45
442	50.1	438.4	489	8 027	9.72	60	60
443	57.1	51.5	109	916	4.55	100	100
444	64.3	432.4	497	8 783	15.37	63	63
445	1 668.0	371.0	2 039	3 374	13.77	100	100
446	42.8	472.2	515	2 281	10.57	21	21
447	62.8	1 513.0	1 576	6 642	9.93	100	100
448	1 194.0	397.0	1 591	12 202	9.97	66	66
449	68.0	418.9	487	5 854	9.90	62	62
450	212.4	420.5	633	4 804	8.08	67	67
451	44.6	450.7	495	2 711	5.09	100	100
452	28.8	175.4	204	10 353	11.37	100	100
453	156.8	435.3	592	11 034	8.05	54	54
454	41.5	255.5	297	6 168	5.97	100	100
455	54.0	408.1	462	9 753	5.89	100	100
456	141.4	436.8	578	8 457	10.99	65	65
457	132.6	583.1	716	12 928	12.23	64	64
458	192.6	999.7	1 192	6 009	14.76	87	87
459	771.6	634.8	1 406	12 384	10.10	36	54
460	253.4	677.6	931	7 411	14.77	87	87
461	203.5	300.3	504	10 332	14.48	80	80
462	1 836.0	245.9	2 082	10 295	11.35	59	59
463	3 760.0	376.0	4 136	8 431	9.79	100	100
464	1 294.0	820.6	2 115	9 775	10.68	70	70
465	160.4	916.1	1 077	3 881	12.06	52	100
466	200.4	970.7	1 171	24 002	6.55	3	3
467	131.1	990.0	1 121	10 180	10.44	79	79
468	223.0	644.5	868	6 133	13.19	69	69
469	4 241.0	289.3	4 530	10 748	9.85	100	100
470	84.7	1 062.0	1 147	8 296	7.50	57	57
471	32.5	149.0	182	1 491	7.96	0	0
472	69.5	109.7	179	5 334	7.37	100	100
473	38.6	230.5	269	3 314	7.97	100	100
474	193.4	430.0	623	10 764	7.68	49	49
475	52.7	351.8	405	8 935	6.33	60	60
476	150.0	1 036.0	1 186	3 798	5.52	54	54
477	177.8	92.7	271	6 736	5.51	22	100
478	161.5	1 083.0	1 245	7 180	6.85	49	49
479	108.2	337.0	445	7 681	10.82	17	38

APPENDIX A. CONTINUED

Fabric #	Potassium ppm	Sodium ppm	Sodium + potassium ppm	Porosity Coresta units	Density oz yd^{-2}	Cotton %	Cellulose %
480	194.6	845.3	1 040	5 661	7.66	0	52
481	88.9	705.6	795	5 652	10.60	0	65
482	185.5	566.3	752	6 403	7.36	44	44
483	77.8	391.3	469	10 242	8.40	0	59
484	70.7	520.1	591	11 406	7.70	0	0
485	26.3	482.0	508	6 844	8.90	3	61
486	56.1	411.3	467	3 608	12.61	28	40
487	1 807.0	317.9	2 125	10 845	12.17	62	62
488	47.5	342.8	390	13 828	12.61	48	48
489	37.1	396.0	433	11 386	12.84	0	72
490	67.5	411.5	479	6 716	8.66	0	100
491	94.1	436.5	531	3 427	12.01	28	40
492	33.0	307.4	340	12 027	13.43	25	49
493	145.1	1 750.0	1 895	4 098	7.65	0	75
494	146.3	406.3	553	18 484	6.60	12	26
495	168.3	425.8	594	7 815	7.50	0	52
496	52.1	315.0	367	7 354	9.63	12	47
497	85.1	364.0	449	10 552	13.22	33	100
498	157.1	428.7	586	10 313	7.34	0	45
499	1 285.0	315.0	1 600	7 769	15.01	53	100
500	51.5	274.5	326	14 412	7.43	0	0

APPENDIX B: IGNITION PROPENSITY RESULTS BY ALL FABRICS, BY CIGARETEE (RESULTS IN % IGNITION)

Fabric #	Cig. type Cig. desig	BNHC25 #519	BELN21 #506	BEHN21 #508	FNLC25 #525	FNHN25 #528
162		100	100	100	100	100
299		100	100	100	100	100
54		100	100	100	100	100
119		100	100	100	100	100
79		100	100	100	100	100
61		100	100	100	100	100
88		100	100	100	100	100
308		100	100	100	100	100
45		100	100	100	100	100
14		100	100	100	100	100
165		100	100	100	100	100
62		100	100	100	100	100
12		100	100	100	100	100
394		100	100	100	100	100
304		100	100	100	100	100
100		100	100	100	100	100
47		100	100	100	100	100
469		100	100	100	100	100
76		100	100	100	100	100
72		100	100	100	100	100
301		100	100	100	100	100
13		100	100	100	100	100
97		100	100	100	100	100
59		100	100	100	100	100
91		100	100	100	100	100
106		100	100	100	100	100
55		100	100	100	100	100
429		100	100	100	100	100
84		100	100	100	100	100
231		100	100	100	100	100
463		100	83	100	100	100
83		100	83	100	100	100
90		100	83	100	100	100
420		100	83	100	100	100
295		100	83	100	100	100
238		100	83	100	100	100
129		100	83	100	100	100
85		100	83	100	100	100
71		100	83	100	100	100
127		100	83	100	100	100
9		100	83	100	100	100
341		100	83	100	100	100

APPENDIX B. CONTINUED

Fabric #	Cig. type Cig. desig	BNHC25 #519	BELN21 #506	BEHN21 #508	FNLC25 #525	FNHN25 #528
262		100	67	100	100	100
445		100	67	100	100	100
136		100	67	100	100	100
46		100	50	100	100	100
107		100	50	100	100	100
87		100	50	100	100	100
19		100	33	100	100	100
314		100	17	100	100	100
86		100	67	83	100	100
499		100	50	83	100	100
66		100	17	83	100	100
148		100	0	83	100	100
245		100	50	67	100	100
78		100	17	67	100	100
1		100	17	67	100	100
155		100	0	67	100	100
283		100	0	67	100	100
419		100	50	50	100	100
105		100	33	50	100	100
70		100	17	50	100	100
34		100	0	50	100	100
42		100	0	50	100	100
164		100	0	50	100	100
74		100	33	33	100	100
37		100	17	33	100	100
68		100	0	33	100	100
15		100	17	17	100	100
147		100	0	0	100	100
140		100	0	0	100	100
252		100	67	83	83	100
67		100	33	50	83	83
293		100	67	100	83	67
7		100	17	0	83	67
26		100	100	100	83	17
276		100	0	50	67	67
108		100	17	33	67	50
246		100	0	50	50	17
57		100	0	17	33	100
121		100	0	17	33	50
407		100	100	0	33	50
448		100	0	17	33	17
447		100	83	67	17	33
264		100	17	83	0	17
239		83	33	33	100	100
38		83	17	0	100	50
110		83	33	17	83	33
49		83	17	33	83	17
287		83	33	83	17	0
118		83	0	0	0	33
135		67	50	50	100	17
24		67	0	17	100	0
40		67	0	17	83	100
256		67	0	0	83	17
247		67	100	67	50	67
289		67	83	100	50	50
151		67	0	33	33	67
65		67	17	50	17	0
122		67	0	0	0	50
146		67	0	0	0	33
77		67	33	67	0	0
120		50	17	67	83	50
150		50	0	0	83	33
349		50	17	0	67	0
159		50	0	0	67	0
138		50	0	0	67	0
141		50	0	0	33	50
81		50	0	0	17	0
103		50	0	0	0	50
391		50	0	17	0	17
64		50	33	100	0	0
131		33	17	0	83	50
302		33	0	17	67	17
169		33	17	17	33	17

APPENDIX B. CONTINUED

Fabric #	Cig. type	BNHC25	BELN21	BEHN21	FNLC25	FNHN25
	Cig. desig	#519	#506	#508	#525	#528
399		33	33	83	0	17
414		33	67	0	0	0
11		33	0	0	0	0
366		33	0	0	0	0
60		33	0	0	0	0
156		33	0	0	0	0
439		33	0	0	0	0
4		17	50	67	67	50
234		17	33	100	67	33
389		17	17	50	50	67
56		17	50	100	33	67
44		17	17	50	33	17
139		17	0	0	33	0
51		17	33	67	17	17
401		17	17	67	17	0
426		17	0	0	17	0
356		17	33	0	0	33
6		17	83	100	0	17
50		17	17	17	0	17
260		17	0	17	0	0
286		17	33	0	0	0
145		17	0	0	0	0
232		17	0	0	0	0
250		17	0	0	0	0
143		17	0	0	0	0
154		17	0	0	0	0
32		17	0	0	0	0
300		17	0	0	0	0
243		17	0	0	0	0
432		17	0	0	0	0

REFERENCES

1. J. F. Krasny, Flammability evaluation methods for textiles. In *Flame-Retardant Polymeric Materials,* Vol. 3, ed. by M. Lewin, S. M. Atlas and E. M. Pearce, pp. 155–200, Plenum, New York, (1982).
2. V. Babrauskas and J. Krasny, *Fire Behavior of Upholstered Furniture,* NBS Monograph 173, Natl Bur. Stands, Gaithersburg, MD, November (1985).
3. M. M. Hirschler, Fire tests and interior furnishings. In *Fire and Flammability of Furnishings and Contents of Buildings,* ASTM E-5 Symposium, 7 December 1992, Miami, FL, ASTM STP 1233, ed. by A. J. Fowell, pp. 7–31, Amer. Soc. Testing and Materials, Philadelphia, PA, (1994).
4. H. Tovey and R. Katz, Involvement of textile products in structure fires: frequency, consequences and causes. Fire Retardant Chemicals Assoc. 1980 Fall Meeting, 'Flame Retardant Needs of the Future: Building and Construction', Pontevedra Beach, FL, 5–8 October 1980, pp. 131–58.
5. A. L. Miller, Where there's smoking there's fire. *NFPA J.,* Jan.-Feb. 86–93 (1991).
6. J. Hall, Items first Ignited in Fires — 1985–1989. Report to NFPA Tech. Cttee on Contents and Furnishings, 17 August 1992, Natl Fire Protection Assoc., Quincy, MA.
7. M. M. Hirschler and S. D. Christian, Fires and the elderly. Fatalities during residential fires in the UK: 1982–84. Interflam'96, Cambridge, UK, 26–28 March 1996, pp. 777–91.
8. ASTM E1352, Standard Test Methods for Cigarette Ignition Resistance of Mock-up Upholstered Furniture Assemblies. Amer. Soc. Testing & Materials, *Annual Book of Standards,* Vol. 04.07, West Conshohocken, PA.
9. ASTM E1353, Standard Test Methods for Cigarette Ignition Resistance of Components of Upholstered Furniture. Amer. Soc. Testing & Materials, *Annual Book of Standards,* Vol. 04.07, West Conshohocken, PA.
10. T. J. Ohlemiller, K. M. Villa, E. Braun, K. R. Eberhardt, R. H. Harris, J. R. Lawson and R. G. Gann, Quantifying the ignition propensity of cigarettes. *Fire and Materials* **19,** 155–70 (1995).
11. T. J. Ohlemiller, K. M. Villa, E. Braun, K. R. Eberhardt, R. H. Harris, J. R. Lawson and R. G. Gann, *Test Methods for Quantifying the Propensity of Cigarettes to Ignite Soft Furnishings.* NIST Special Publication 851, Natl Inst. Stands Technology, Gaithersburg, MD (1993).
12. Cigarette Safety Act of 1984, Public Law 98–567, 30 October 1984.
13. R. G. Gann, E. Press, C. M. Carey, J. L. Charles, J. W. Cullen, J. C. Gerard, J. F. Hoebel, P. H. Leake, M. D. McGibeny, A. McGuire, W. H. Poel, A. W. Spears, H. Tovey, D. E. Townsend and J. P. Wilkenfeld, *Toward a Less Fire-Prone Cigarette. Final Report of the Technical Study Group on Cigarette and Little Cigar Fire Safety,* Consumer Product Safety Commission, Washington, DC, October (1987).
14. R. G. Gann, R. H. Harris, J. Krasny, R. Levine, H. Mitler and T. J. Ohlemiller, *The Effect of Cigarette Characterstics on the Ignition of Soft Furnishings,* NBS Technical Note 1241, Natl Bur. Stands, Gaithersburg, MD (1987).
15. R. G. Gann, R. H. Harris, J. Krasny, R. Levine, H. Mitler and T. J. Ohlemiller, The effect of cigarette characteristics on the ignition of soft furnishings. Part 3 of Final Report of Technical Study Group, Cigarette Safety Act of 1984, Consumer Product Safety Commission, Washington, DC (1987).
16. Fire Safe Cigarette Act of 1990, Public Law 101–352, 10 August 1990.
17. R. G. Gann, J. Adams, C. M. Carey, J. C. Gerard, J. F. Hoebel, M. D. McGibeny, A. McGuire, D. O. Pinion, E. Press, D. Shopland, A. W. Spears, D. E. Townsend, J. F. Whidby, J. P. Wilkenfeld and J. M. Williams, Overview: practicability of developing a performance standard to reduce cigarette ignition propensity, Part 1 of Final Report of the Technical Advisory Group on the Fire Safe Act of 1990. Consumer Product Safety Commission, Washington, DC, August (1993).

18. M. M. Hirschler, Repeatability and reproducibility of fire tests for cigarette ignition of upholstered furniture composites. *Fire and Materials,* submitted.
19. R. W. Dwyer, L. G. Fournier, L. S. Lewis, D. Furin, A. M. Ihrig, S. Smith, W. Z. Hudson, R. H. Honeycutt and J. E. Bunch, The effects of upholstery fabric properties on fabric ignitabilities by smoldering cigarettes. *J. Fire Sciences* **12**, 268–83 (1994).
20. R. G. Gann, private communication.
21. A. W. Spears, Factors not considered by N.I.S.T. in the proposed test methods. Attachment to *"Report of the Cigarette Ignition Propensity Joint Venture to the Consumer Product Safety Commission",* July 1993, Washington, DC.
22. M. M. Hirschler, Mathematical models to analyse the effect of physical properties of cigarettes on the propensity of the cigarette to ignite cellulosic fabrics. *Fire and Materials* **21**, 33 (1997).
23. A. W. Spears, A. L. Rhyne and V. Norman, Factors for consideration in a test for cigarette ignition propensity on soft furnishings. *J. Fire Sciences* **13**, 59–84 (1995).
24. M. M. Hirschler and T. Piansay, Fabric flammability. Survey of flame spread of modern fabrics. Business Communications Company 7th Conference on Recent Advances in Flame Retardancy of Polymeric Materials, 20–22 May 1996, Stamford, CT, ed. by M. Lewin, Norwalk, CT (1996).

ATTACHMENT 5

Forensic Evaluations of Fabric Flammability

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ABSTRACT

Seventeen commercial garments were purchased, analyzed as to their fabric composition and fire tested. Three fire exposures were used: (a) a simile of 16CFR1610, (b) a small vertical candle on a small swatch of fabric and (c) a candle applied to a full garment, placed on a mannequin. Comparisons were made between the results of the various tests and of the various fabrics tested. A general correlation was observed whereby increased fabric areal density [weight/unit fabric area] resulted in improved fire performance. Where outliers to this generalization were observed the improved fire performance was due to the superior inherent fire performance of specific fabric types such as silk. Overall, the quantitative behavior with regard to flame spread rate observed after ignition of cellulosic, thermoplastic and blended fabrics, was more heavily dependent on fabric areal density than on their chemical composition. It is also observed that very lightweight fabrics constitute a potential danger and that the regulatory value of 2.6 oz/yd^2 represents an essentially arbitrary cut-off in this regard.

INTRODUCTION

Clothing worn by people rarely ignites. There were an average of 520 fires ignited on clothing worn by a person, causing 120 fire fatalities and 149 fire insjuries per year over the period 1999-2002, and such fires have been decreasing in recent years [1]. However, when fires do occur while clothing is worn by an individual, the results can be catastrophic!

As the preceding data illustrate, the ratio of fires to fire fatalities in worn apparel is 4.3. This ratio is much worse than the ratio for other textile consumer products frequently involved in fires such as upholstered furniture (17.7), mattresses (42.3), floor coverings (69.7), curtains and drapes (153.5) or clothing not on a person (161.5) [1]. The items discussed in this paragraph are, in fact, far more likely to be involved in fires than clothing fabrics.

When apparel fires do occur, an effort is often made by the victims in such incidents to evaluate the clothing involved to determine whether the clothing item or items involved were at fault and/or those items behaved in an unexpected or unreasonably dangerous manner. Given the low frequency of such events, *when* such retrospective evaluations are made, they frequently are part of a forensic or product liability evaluation. Such analyses are, by their nature, different from those which are a part of a controlled, experimentally designed series of activities consistent with prospective research. In contrast then, these forensic evaluations are driven by retrospective events and frequently lack controls which are often key to conducting comprehensive scientific research.

The authors were recently involved in a forensic evaluation of clothing fabrics. As a result, they have developed further evaluations of certain generalizations about fabric flammability made frequently in regard to fabrics used in clothing. These included assessing whether or not certain classes of fabrics were inherently more safe than others and assessing whether the underlying applicable Federal Regulations in place in the United States provide adequate minimum standards for the safety of apparel or clothing sold in the US. This is of particular interest given the age of the regulations and their simple nature. It is the objective of this article to consider and review some of these points for interested readers.

BACKGROUND

Regulation on apparel flammability:

Since the 1950's clothing sold in the United States has been evaluated for flammability performance in accordance with 16CFR1610 (Standard for The Flammability of Clothing Textiles [2]. This standard, also known as CS-191-53, was enacted by Congress in 1953 and is currently administered by the US Consumer Product Safety Commission [CPSC]. In this test, samples tested are placed in a sample holder at a 45 degree angle, and the igniter flame is imposed on the upper surface of the sample. The test method requires that replicate, pre-conditioned samples of fabrics used in clothing apparel comply with one of the following criteria:

(a) no ignition when subjected to a small gas diffusion flame emitted from a burner based on a hypodermic needle during an exposure of 1.0 s, or

(b) if the fabric sample ignites, the flames shall not spread 5 inches in less than 3.5 seconds.

The regulation addresses the sensitivity of this test method to fabric weight (or areal density) by providing that fabrics with areal densities in excess of 2.6 oz/yd^2 (roughly 60 g/m^2) be excluded from testing. These are considered too heavy to ignite under the test conditions.[1]

Many opinions – both pro and con - have been written about the 16CFR1610 regulation and the CS 191-53 test method. Such statements come both from within the fire safety community and from others more peripherally involved in fire safety practice. There is a diversity of opinions as to the adequacy of the regulations in place.

Opposition to the 16CFR1610 test:

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[1] 16CFR1610 states: 1610.62 (4) Note 2 - Some textiles never exhibit unusual burning characteristics and need not be tested. 16CFR 1610.37(d). Such textiles include plain surface fabrics, regardless of fiber content, weighing 2.6 oz. or more per sq. yd., and plain and raised surface fabrics made of acrylic, modacrylic, nylon, olefin, polyester, wool, or any combination of these fibers, regardless of weight.

A favorite criticism of this test method, for example, is that ordinary newsprint, and even tissue paper, will meet its requirements (see Figure 1 with a photograph of a test with paper after 2 s).

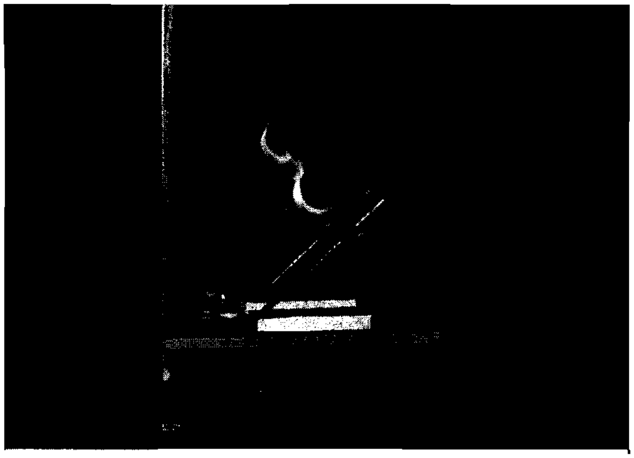

Figure 1: Paper Tested in Simulated 16 CFR 1610 Test after 2 s

One issue where there does seem to be general agreement upon, however, is that, in spite of its lack of sophistication, this test method has been successful in screening out the "worst actors" from the general population of fabrics in use for apparel. Thus, fabric types such as the fibrous "torch" sweaters with raised surface fibers that ignite readily and spread flame quickly are no longer legally sold in the United States due to the test requirements. The test has also been able to screen out very sheer fabrics, including ones used for scarves and frequently imported, ultra-light cotton garments, or other garments that are not made of acrylic, modacrylic, nylon, olefin, polyester, wool, or any combination of these fibers.

Much of past and current state of the art is encapsulated in the following comment by the late Howard Needles, a frequent consulting expert in fabric flammability, personal injury actions. He stated [3]:

"Although the flammability standard for general wearing apparel designated 16CFR1610 has effectively removed extremely flammable fabrics from the market place, significant numbers of children and older adults are burned when their lightweight, loose fitting clothing made from 100% cellulosic or polyester cellulosic blend fabrics catches fire."

As such, Dr. Needles has made a case that the the 16CFR1610 standard is generally adequate, but that, based on his observations of the issues, a case can be made that certain segments of the population - principally the very young and the very old - are put at particular risk by the standard. Dr. Needles' comments are also typical of the position consistently taken by some forensic experts critical of the use of the 16CFR1610 regulation. Similar comments also are often made addressing the adequacy of lightweight fabrics such as cotton, thermoplastics and cotton-polyester blends since the

1970s. A particular subset of the contentious apparel flammability issue relates to children's sleepwear and the specific governing Federal standard for that class of clothing, which is addressed later in this article.

Support of the 16CFR1610 requirements:

At the other end of the spectrum to the holders of the opinions described above are forensic experts who completely ignore the added frequency of fire injuries or fire fatalities in the age classes above. Such experts suggest that regulations and/or requirements additional to those already mandated in the general apparel and children's sleepwear standards are unnecessary. These sort of comments are included in proceedings of symposia addressing textile flammability [4], as well as several other articles which discuss state of the art in fabric flammability testing as well as the importance of fabric labeling issues [5-9].

Scientific Approach to Apparel Requirements and 16CFR1610:

Irrespective of opinions regarding fabric flammability issues, four key factors tend to be of importance when considering the possible severity of a fire when a fabric in a garment becomes ignited. These are:

(a) the weight/unit area of the fabric [its "areal" density],
(b) the composition of the fabric,
(c) the design of the item of clothing and
(d) the type of wearer of the garment.

(a) It is generally well-known that the higher the areal density of the fabric (usually referred to as the "weight") the lower its flame spread potential. This is consistent with what is known for all flammability issues: denser materials are more difficult to ignite and burn less vigorously. The effect of fabric fabric areal density will be discussed in greater detail in the remainder of this work.

(b) Similarly, it is also generally well known that some materials have better flammability properties than others (see for example, Cullis and Hirschler [10]). "Better flammability properties" can be represented by a lower ease of ignition (for example, a longer time to ignition with the same ignition source), a lower tendency to spread flame or a lower heat release rate. Another characteristic that is inherent in the composition of the fabric is the difference between charring fabrics and thermoplastic fabrics. Thus, for example, charring fabrics (such as those based on cellulose) burn very differently from thermoplastic fabrics (such as those based on polyester or nylon) since the latter class tend to melt and drip rather than burn in place leaving a residue. The effect of fabric chemical composition will also be discussed in greater detail in the remainder of this work.

(c) In terms of garment design, a key difference affecting fire performance is whether a garment is designed to be worn in tight-fitting or loose-fitting modes. Garments that cling to the skin (i.e. that are tight-fitting) will burn, and spread flame, quite differently from those that hang loosely from a wearer's body. This is because loose-fitting garments will readily experience flame spread on *both* sides of the fabric more or less simultaneously, while tight-fitting garments will spread flame primarily on a single side, namely the side *away* from the wearer. The ways in which the combination of physical and chemical properties of a given fabric used in the design of a similar garment is illustrated in the following example: when a loose-fitting cotton (charring) garment is ignited, it can burn on both sides and spread flame vertically. On the other hand, when the equivalent loose-fitting polyester garment is ignited it may melt into a victim's skin, potentially resulting in contact burns.

These garment properties have been applied in the promulgation of the Children's Sleepwear Regulations [11]: whereby garments must be made of

i. a thermoplastic fiber or
ii. a flame retarded cotton fiber or
iii. be tight fitting.

The use of tight-fitting thermoplastic-based children's pajamas is a good example of effective design for fire safety, as discussed above. Moreover, loose-fitting designs, such as nightgowns or long tee-shirts, which may even have buttoned collars and/or sleeves, are hard to remove in an emergency.

(d) A final key factor affecting fire hazard is the age of the wearer (as well as his/her physical and mental capability). It has long been known that the elderly and the very young are at higher risk than the general population in terms of fire incidence and incidence of injuries or fatalities [See for example 12-17]. Figure 2 illustrates this [17].

Fabric Flammability - Additional Issues:

It is important to note that simply lumping fabrics into categories associated with charring versus melting behavior is not enough. There are fabrics, such as thermosetting fabrics, that do not easily fall into either category. Moreover, blends of fabrics based on a charring material (such as a cellulosic) and a thermoplastic (such as a polyester) are very commonly used, and their fire performance will be neither that of a charring or of a melting fabric. Rather the observed performance of the fabric will be some function of the composition of each type of fabric in the blend combined.

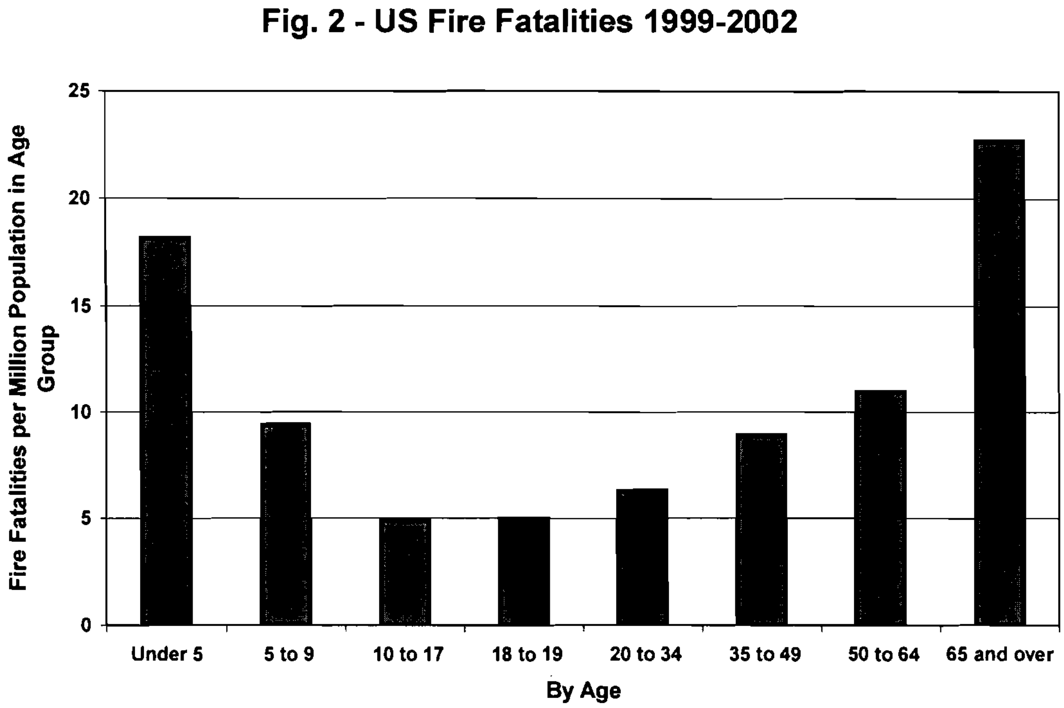

Figure 1: Fire fatalities in the United States - 1999-2002 [17]

A final note of introduction to fabric flammability regulation: With the exception of the enactment of the Children's Sleepwear Standard (in 1972 and 1975), and its revisions, neither Congress nor the CPSC have made any significant changes in terms of the required standards for apparel flammability. One reason for this lack of activity appears to be a concern that increased regulations for fire safety of wearing apparel - without careful consideration of the consequences - will result in a reduction of consumer choices in comfort, without perhaps ensuring a higher degree of safety. However, there may still be the need for some changes that would improve the ease of elimination of "bad actors".

ANALYSES CONDUCTED

In the case leading to our conducting the research reported here, an adult woman was injured when the skirt she was wearing ignited and burned causing life threatening injuries. No exemplar or identifiable residue of the incident skirt was available, which is reasonably common in fabric flammability evaluations in forensic situations. In the absence such materials, tests were conducted by experts for both plaintiff and defendant in the hope of finding correlations from among different possible types and combinations of fabrics and of test methods. Properties of these textile fabrics (density, composition) and associated combustion related characteristics (such as time to sustained flaming and burning rates observed) were studied in order to address issues of likely real scale performance if the fabric were to be able to be identified with specificity. In addition real scale testing of skirts fabricated from these fabrics was conducted and the results were compared with findings based on 16CFR1610 style testing.

EXPERIMENTAL

Three different types of flammability tests were conducted: (a) hypodermic burner ignition tests similar to 16CFR1610, (b) vertical burn tests of free hanging fabric swatches ignited by a candle, and (c) full scale burn tests with clothing on a mannequin. All fabrics tested came from garments purchased from local department stores.

The first set of garments evaluated (set A) contained 9 pieces of clothing covering a broad range of fabric areal densities. The second set (set B) contained 8 garments, all of which were manufactured from fabric blends. In total, 17 garments were evaluated.

Table 1 provides a breakdown of the clothing tested and identification used.

16CFR1610 simulation:

The 16CFR1610 simulation_involved utilizing the major components of the 16CFR1610 test equipment:

- time of exposure,
- placement of fabric specimen (45 degree angle),
- exposure gas type [butane gas]
- exposure intensity [gas issued from a 26 gauge hypodermic needle burner].

However, the equipment used for the testing lacked the specific automatic features of commercially available testing equipment normally used to conduct 16CFR1610 testing. Each fabric tested was evaluated using duplicate 2 in. x 6 in. specimens. Prior to cutting the test specimens, weight and area of the fabric in each garment was evaluated, by obtaining a planar swatch, to assess areal density.

For testing the hypodermic needle and polymeric tubing were routed through a 0.25 in., 90 degree metal tube and were installed through the bottom of the testing platform. This enabled the needle to be fixed parallel to the platform, while retaining an ability to rotate in that plane. The rotational ability allowed the ignition of the flame prior to fabric testing so that the flame length could be adjusted to the requisite 5/8 in. prior to exposing the fabric to the igniter flame. The fabric holder-mounting surface was comprised of two thin aluminum plates (1/16 in. in thickness) each having a length of 7 in. and a width of 0.5 in.. The plates were connected together so that the separation width was 1.5 in.; the bottom section had no cross member, while the top did. The plates were designed to make a 45-degree angle with respect to the horizontal surface. Figure 3 shows a specimen with relatively good fire performance burning in the apparatus.

The fabric length was equal to the length of the holder, so that the fabric laid flush from the bottom edge to the top. The butane-fueled flame was set at a height of 1.0 in. above the bottom edge of the fabric (1.41 in. vertical height). The placement of the flame above the leading edge of the fabric allowed for a more uniform flame impingement, reducing effects due to fabric orientation from cutting, material composition, and thickness. The flame growth rate was timed between the height of flame impingement (1.0 in.) to the 6.0 in. length of the fabric, which left 1.0 in. of fabric on the top side. This allowed for a total burn time to be measured with the flame spreading a total of 5.0 in. The width of the fabric was designed so that the middle portion, which is consumed in the flaming combustion, has a width of 1.5 in.. The fabric sample has a total width of 2.0 in., which leaves 0.25 in. overlap on each side of the fabric holder.

Once the fabric had been mounted and flame length adjusted, the hypodermic needle was rotated to point directly at the fabric for 1.0 seconds consistent with the requirements of 16CFR1610. If the fabric ignited and self sustained flaming resulted, the fire was allowed to spread until it either self-extinguished or consumed the sample. If the fabric did not ignite after 1 second, the butane flame was reapplied until ignition occurred [a condition designated here as "forced ignition"]. In all cases, time to ignition and elapsed time for the flame to spread 5 in. were recorded.

In Figure 3, the hypodermic needle has been rotated away form the fabric and flaming combustion is self-sustaining, after a 3 s forced ignition. In the photo, it is possible to see the markings on the frame after each inch; 2 white horizontal lines were also marked on the fabric at the lengths of 1.0 in. and 6.0 in.

Vertical burn test:

The vertical burn test used assessed the fire performance of the fabrics hanging freely, using a 2.0 in. wide metal clip from an adjustable height rod. This exposure utilized an "All Purpose Emergency Candle [19 mm x 127 mm]" made by Candle-lite, model number 3745 as an ignition source. During testing, the candle was initially held under the free hanging fabric for a period of 1.0 s. Similarly to the 16CFR1610 simulation (or 45 degree angle test), if sustained flaming did not occur, the candle flame was reapplied until ignition of the textile occurred. The time required to bring the fabric to flaming combustion and for the first 5.0" in. to be consumed were then recorded. (See Figures 4 and 5 for photos of test set-up).

It is worth noting, as illustrated in Figure 6, that the intensity of the candle is less consistent than that of the 16CFR1610 hypodermic needle flame, but is in the same range.

Table 1 - List of apparel purchased, with composition, price and areal density

Item #	Type of Garment	Color	Fiber 1	Fiber 2	Fiber 3	Fiber 4	Price ($)	Density (g/m^2)
A-1	Scarf	Black	100% Silk				16.00	33
A-2	Scarf	Multicolored	100% Polyester				28.00	46
A-3	Blouse	White Pink striped	100% Cotton				20.00	106
A-4	Dress	Navy blue & white	100% Polyester				34.65	215
A-5	Blouse	Brown & gold	90% Polyester	10% Spandex			12.60	235
A-6	Trousers	Black	100% Rayon				39.50	256
A-7	Top/Tee Shirt	Blue stripes dark/light	77% Silk	20% Nylon	3% Spandex		27.65	258
A-8	Skirt	Red	97% Cotton	3% Spandex			31.15	302
A-9	Jeans	Blue	100% Cotton				50.00	466
B1	Sun Dress	Blue/white	65% Rayon	23% Polyester	12% Linen		11.99	81
B-2	Dress Lining	White & Pink flowers	65% Polyester	35% Cotton		(Dress is 100% cotton)	7.99	116
B-3	Sleeved Dress	Grey	68% Polyester	32% Rayon			8.00	141
B-4	Nightgown	Pink	65% Modal	35% Polyester			76.00	169
B-5	Party Dress	Beige	51% Rayon	39% Nylon	7% Spandex	3% Polyester	9.99	176
B-6	Sleeveless Dress	Grey	50% Poly	50% Cotton			12.00	247
B-7	Skirt	Black	62% Polyester	34% Rayon	4% Spandex		42.00	324
B-8	Dress	Black	65% Rayon	35% Nylon			14.99	419

Mannequin test:

For this set of trials, a female styled mannequin was clothed using the 8 items of apparel composing set B [2]. In each trial, a garment was ignited at a lower rear portion of the item using the same candle ignition source as was utilized in the vertical burn test. Testing was done indoors, in a location sheltered from the wind and other adverse environmental conditions.

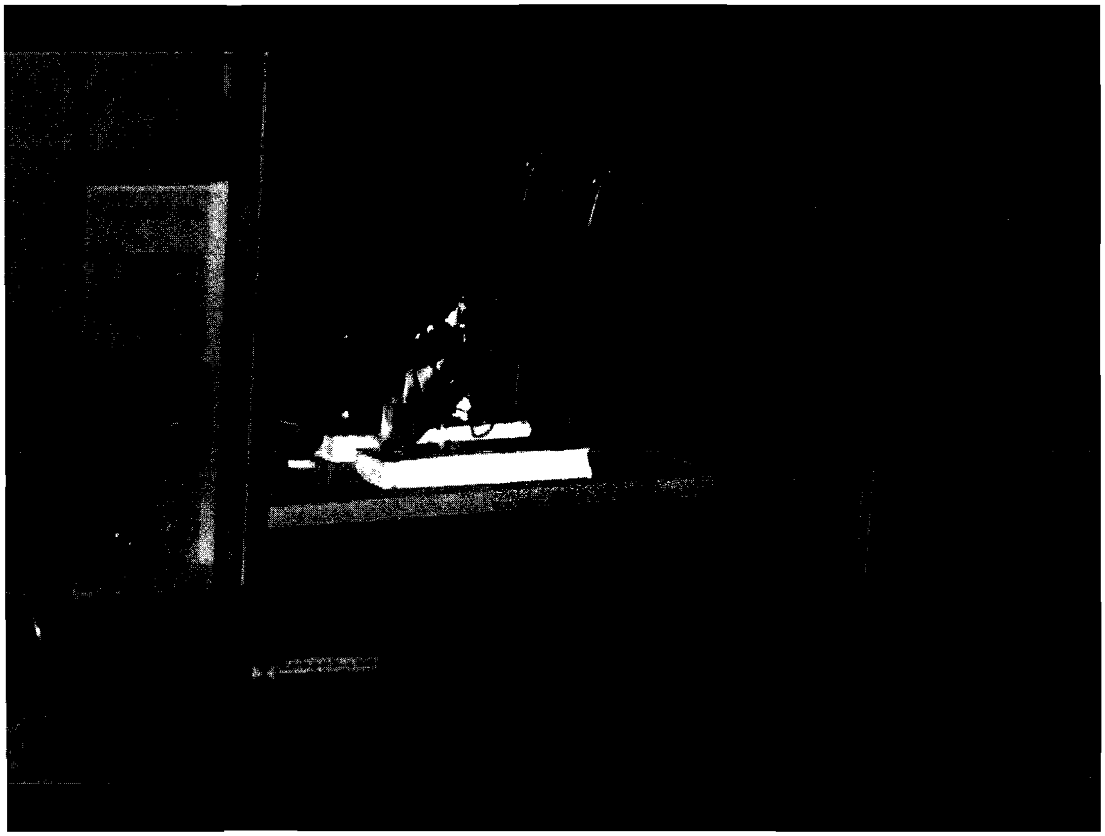

Figure 3. 16CFR1610 Test on Fabric A-5, after flame removal

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[2] Prior to this, 4 in. by 7 in. swatches had been cut, from an edge of each garment for evaluation by the two previously-described test methods.

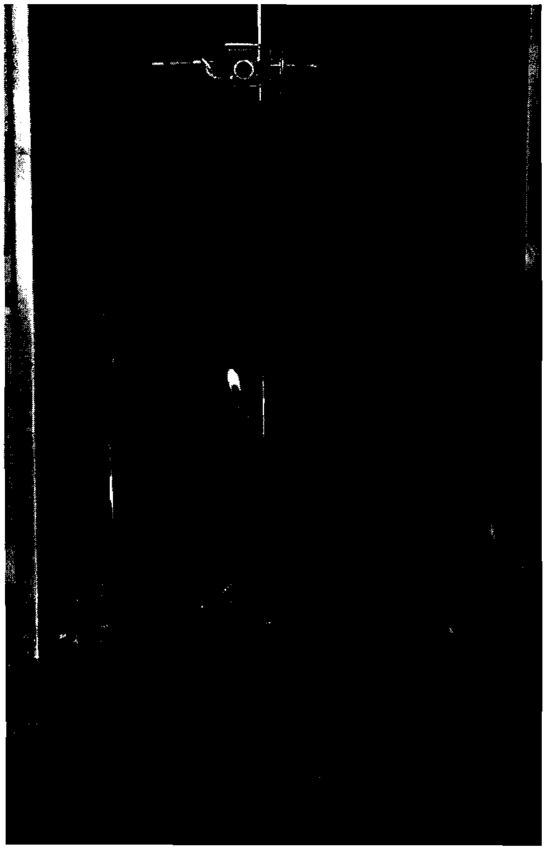

Figure 4: Test on fabric B8 (2 s candle)

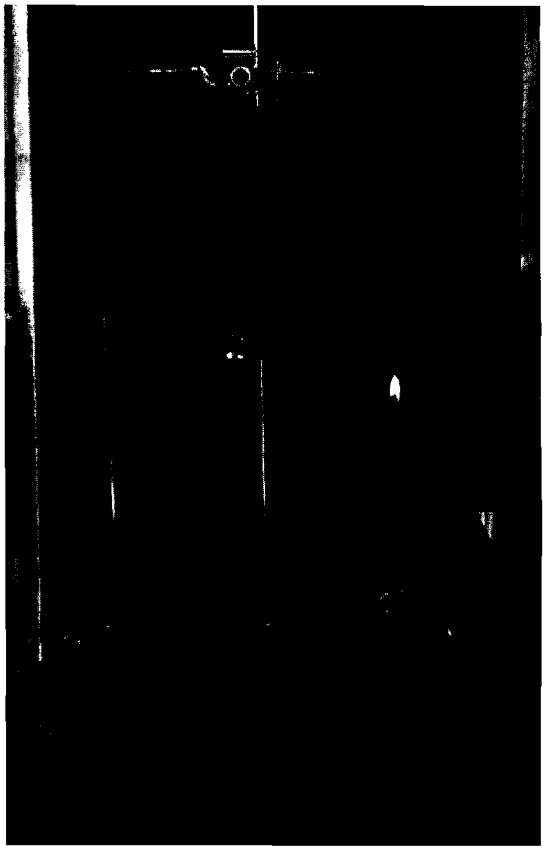

Figure 5: Test on fabric B8; candle removed

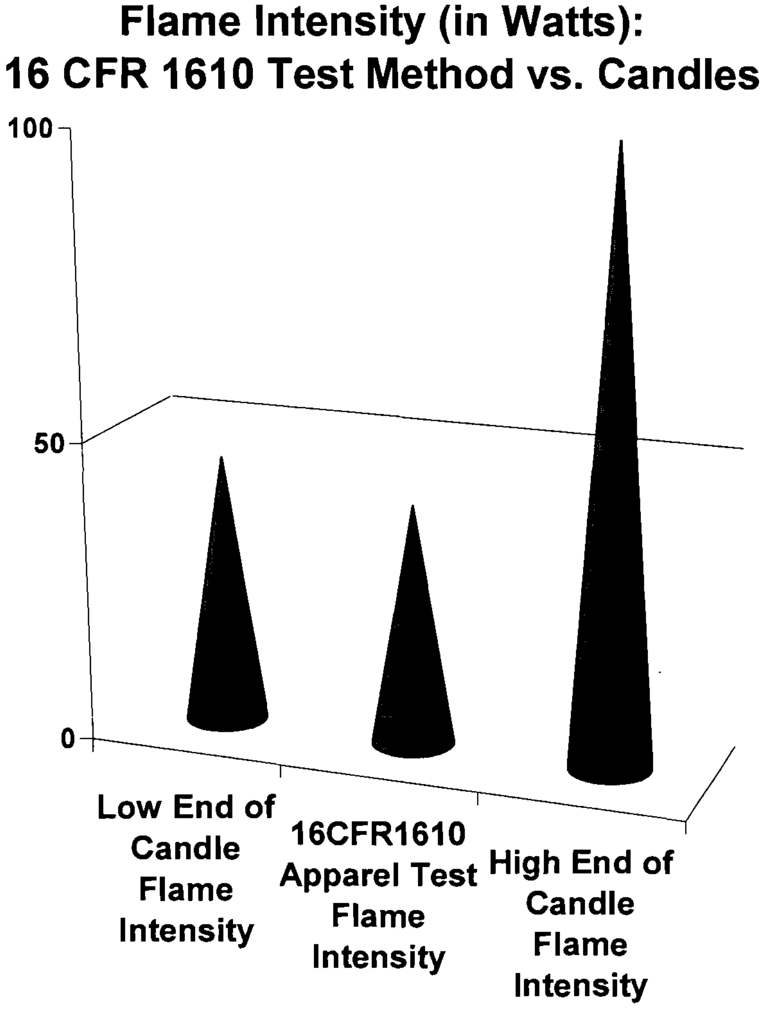

Figure 6: Flame Intensity of 16 CFR 1610 Test and Candles

In some cases, items self-extinguished, and were reignited using the candle. This set of trials was observed to be the least quantitative of the three testing scenarios/evaluation schemes. However, it was still possible to obtain a variety of critical times and other fire performance observations, which were noted (see Tables 2 and 3) during each trial. Figures 7 and 8 illustrate the range of performance observed in two different garments, one with fairly poor fire behavior (B1) and one with reasonable fire behavior (B8).

The data collected from the three series of tests are summarized in Tables 2 and 3.

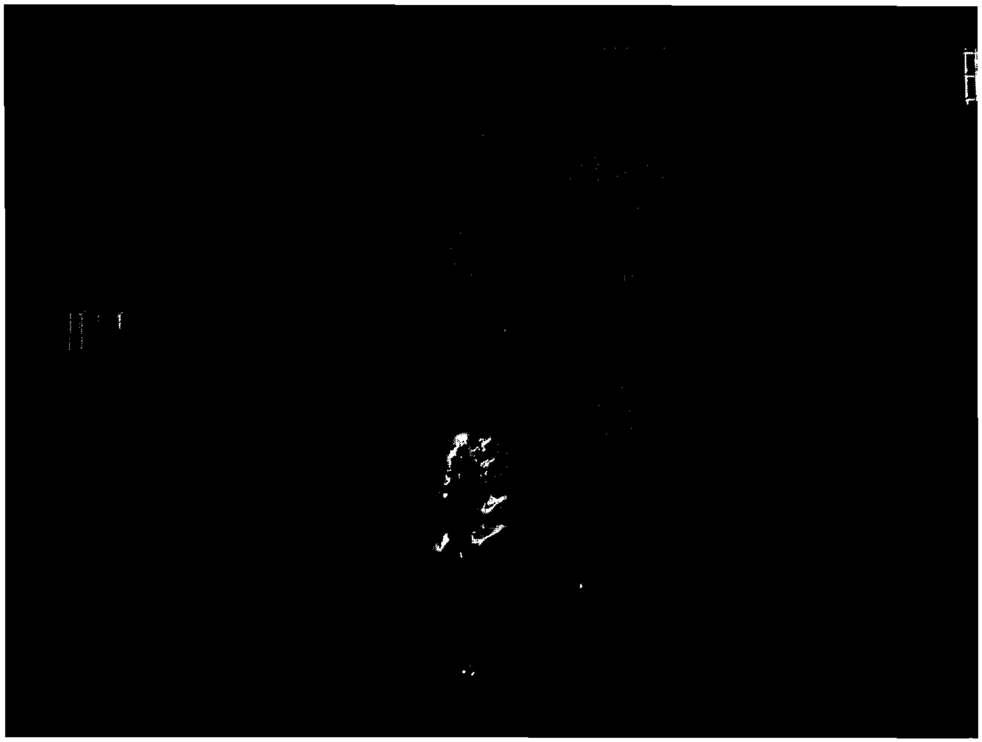

Figure 7: Mannequin test on B1 dress after 41 s.

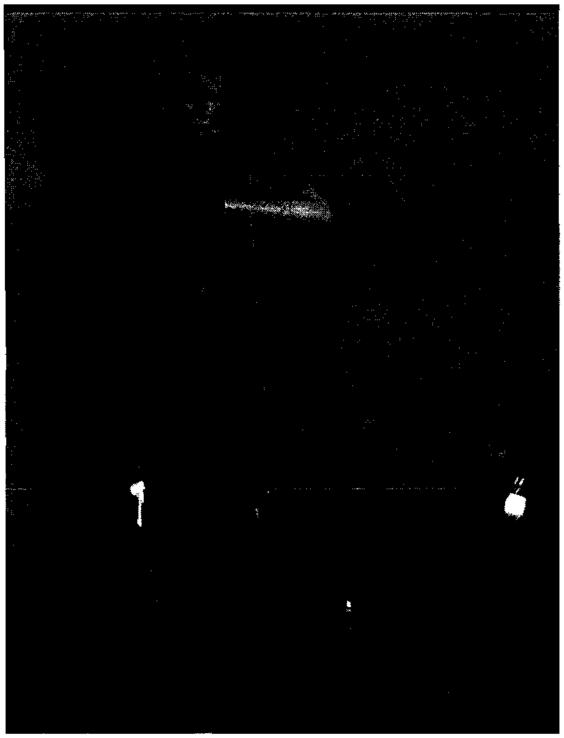

Figure 8: Mannequin test on B8 dress after 4 min 17 s.

TABLE 2 - Major Fire Test Results
(The Garments are Listed in Order of Increasing Fabric Areal Density)

			16CFR1610 Simulation		Candle Vertical Ignition		Mannequin test	
Item #	**Type of Garment**	**Areal Density (g/m^2)**	**Time to Ignition (s)**	**Time for Flame to spread 5 in (s)**	**Forced Ignition for x s**	**Time for flame to spread 5 in (s)**	**Time for Flame to waist (s)**	**Time for Flame to shoulder (s)**
A-1	Scarf	33	2	9	2	15	N/A	N/A
A-2	Scarf	46	2	9	1	7	N/A	N/A
B-1	Sun Dress	81	1	14	1	Melt drip & extinguish @ 4 s	43	60
A-3	Blouse	106	3	16	1	8	N/A	N/A
B-2	Dress Lining	116	2	20	1	12	33	72
B-3	Sleeved Dress	141	2	9	1	12	14	47
B-4	Nightgown	169	4	16	1	19	38	47
B-5	Party Dress	176	3	18	1	18	33	36
A-4	Dress	215	2	27	4	30	N/A	N/A
A-5	Blouse	235	4	32	3	35	N/A	N/A
B-6	Sleeveless Dress	247	4	Does not occur	4	42	Does not occur	Does not occur
A-6	Trousers	256	5	40	1	17	N/A	N/A
A-7	Top/Tee Shirt	258	5	Does not occur	2	32	N/A	N/A
A-8	Skirt	302	5	109	1	27	N/A	N/A
B-7	Skirt	324	6	34	1	30	65	95
B-8	Dress	419	9	123	2	46	43	Does not occur
A-9	Jeans	466	7	205	3	40	N/A	N/A

TABLE 3 - Additional Fire Test Results, Mannequin Tests

Item #	Type of Garment	Areal Density (g/m^2)	Smoke @ (s)/Color	Flaming Drips @ (s)	Flaming Large Debris @ (s)	Self extinction or Manual extinction @ (s)	Charring Evidence @ (s)	Fraction of Garment Remaining (%)
B-1	Sun Dress	81	13 grey	23	70	M 95	None	0
B-2	Dress Lining	116	12 black	51	58	M 180	120	0
B-3	Sleeved Dress	141	22 grey	20	40	M 100	None	0
B-4	Nightgown	169	25 grey	55	70	M 145	None	0
B-5	Party Dress	176	60 black	65	65	M 180	None	20
B-6	Sleeveless Dress	247	No smoke	64	None	S 75	None	95
B-7	Skirt	324	41 grey	120	None	M 240	100	30
B-8	Dress	419	23 white	Does not occur	None	M 500	145	70

DISCUSSION

The information collected provided data inputs for an analysis which compared exposure regime with type of fabric testing. The data also allowed the authors to prepare correlations between textile properties and their ignition and flame spread characteristics. Figure 9 illustrates a comparison between the times for the flame to spread 5 in. in the simulated 16CFR1610 trials versus the areal density of each fabric evaluated. That data shows a fairly reasonable correlation to exist between the data for these two properties, but the relationship is not linear.

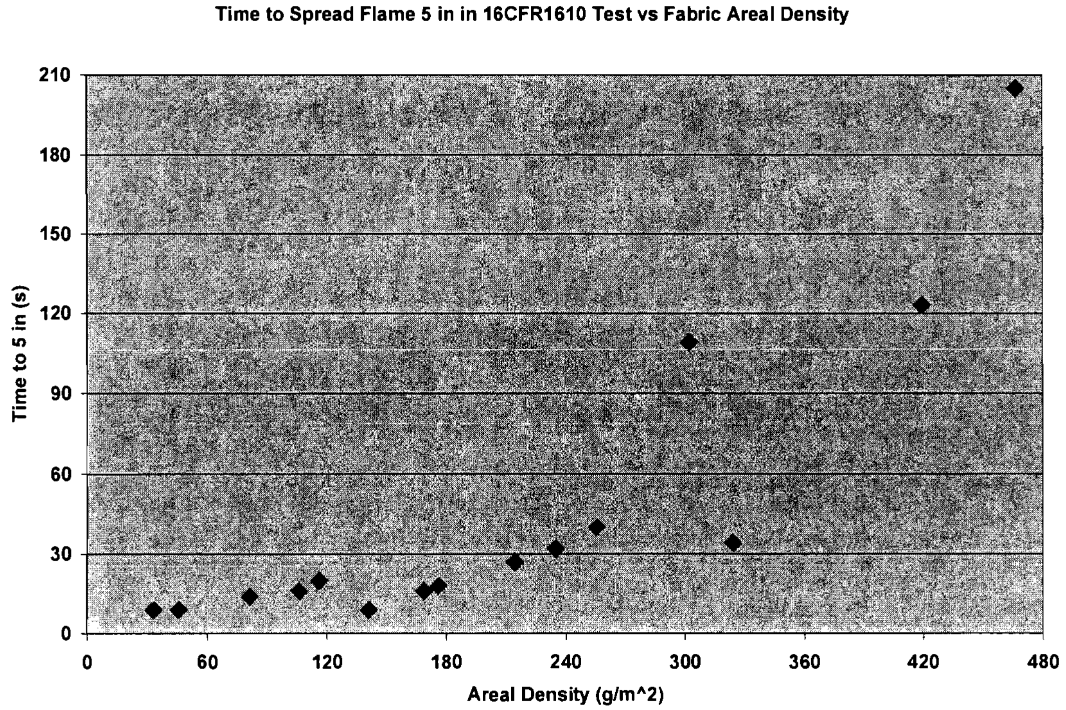

Figure 9: Relation between the time for the flame to spread 5 in. in 16CFR1610 test and areal density (2 specimens did not display spread flame the full 5 in. and were excluded from the graph)

Table 4 presents rankings for fabrics tested based on the following properties observed: (1.) areal density (weight per unit area) as tested, (2.) time for the flame to spread 5 in. in the 16CFR1610 simulation, (3) time needed to obtain forced ignition in the 16CFR1610 simulation, and rankings based on fire performance in the (4) vertical candle small scale test and (5) the mannequin test.

Figure 10 compares the three first-named sets of these rankings graphically, and shows that they are well correlated.

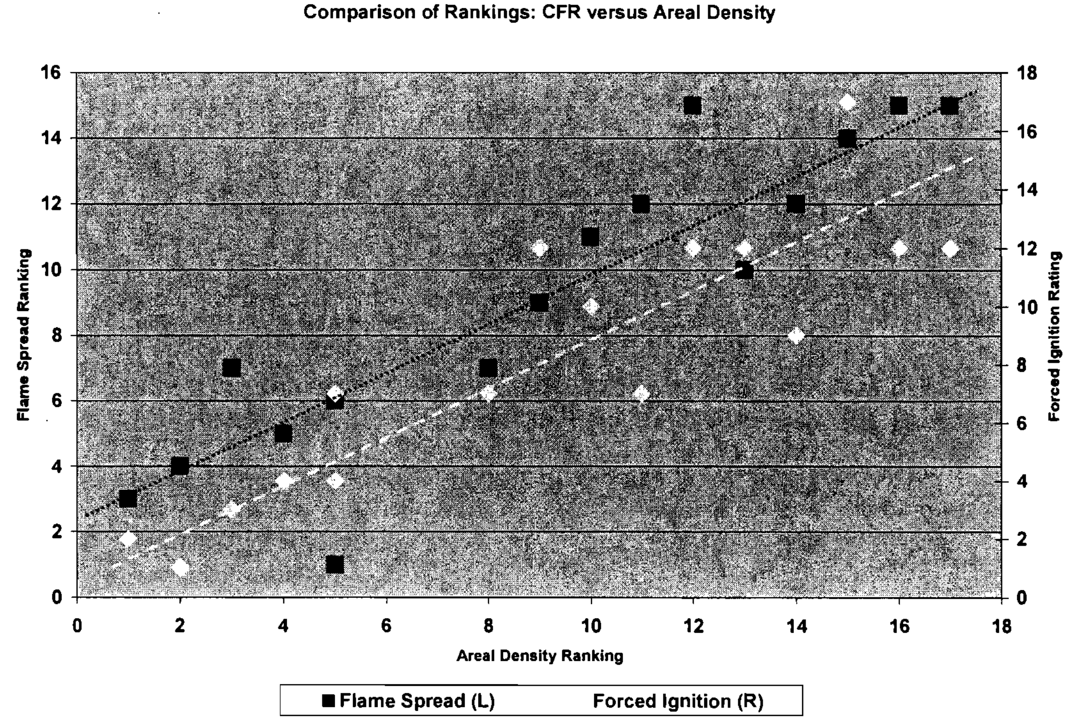

Figure 10: Comparison of rankings on the time for the flame to spread 5 in. and forced time to ignition, both in 16CFR1610 test with rankings on areal density

The information above is not entirely surprising, as similar analyses [see Figures 11 thru 15] of earlier data reported by Howard Needles [18], J.W. Weaver [6] and Marcelo Hirschler [19], after analysis by the present authors for this work, showed similar trends. Specifically, Howard Needles generated forced ignition data using the 16CFR1610 test, with a variety of all-cellulosic fabrics, and measured the time for the flame to spread to 5 in. (Figure 11). Weaver did the same for a variety of cotton and non-cotton fabrics using the same test method, which he referred to as the CS 191-53 test. These are shown in Figure 12, for the cotton fabrics, and Figure 13, for all fabrics. A combination of the Needles and Weaver data is shown in Figure 14. Marcelo Hirschler tested a series of fabrics using the small scale version of the NFPA 701 vertical fabric test [20] and Figure 15 shows the time to spread flame all the way to the top (6 in.) plotted against fabric areal density.

The data presented indicate clearly that there is a general trend, *for all textiles*, such that as areal density increases, times to ignition and times for flame to spread to a certain location (in this case the top of a sample) also increase. It is important to note that the fabric areal density (or fabric weight) data used for the plot in Figure 10 included all fabrics, irrespective of their fabric composition (independent also, thus, of the fuel value of the fabrics). This means that clear correlations were found between fire performance of the fabrics and fabric areal density data alone, irrespective of the fuel value of the fabrics studied. Consequently, the correlation is the same, independent of the nature of the types of polymer the fabrics are made of. However, fabric fuel value *does* play a key role in understanding the fire performance of certain fabrics. Thus, for example, some fabrics performed much better than their areal density would suggest (like the silk scarf) because of the inherent excellent flammability performance of the polymer, namely silk.

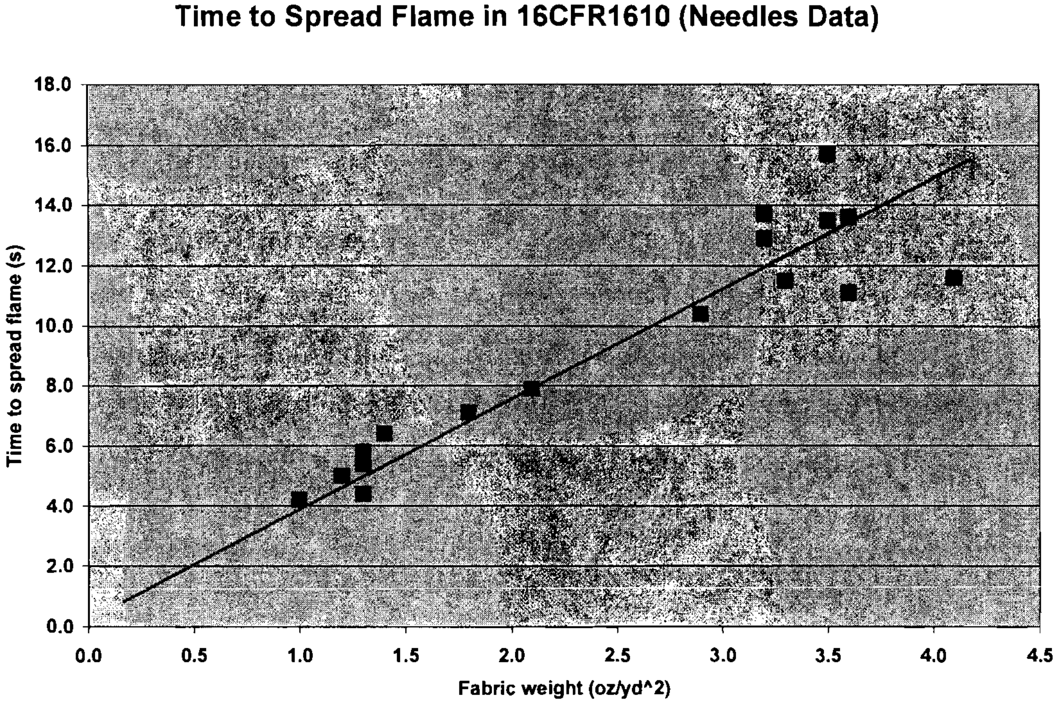

Figure 11: Howard Needles [18] time to flame spread data plotted against fabric weight.

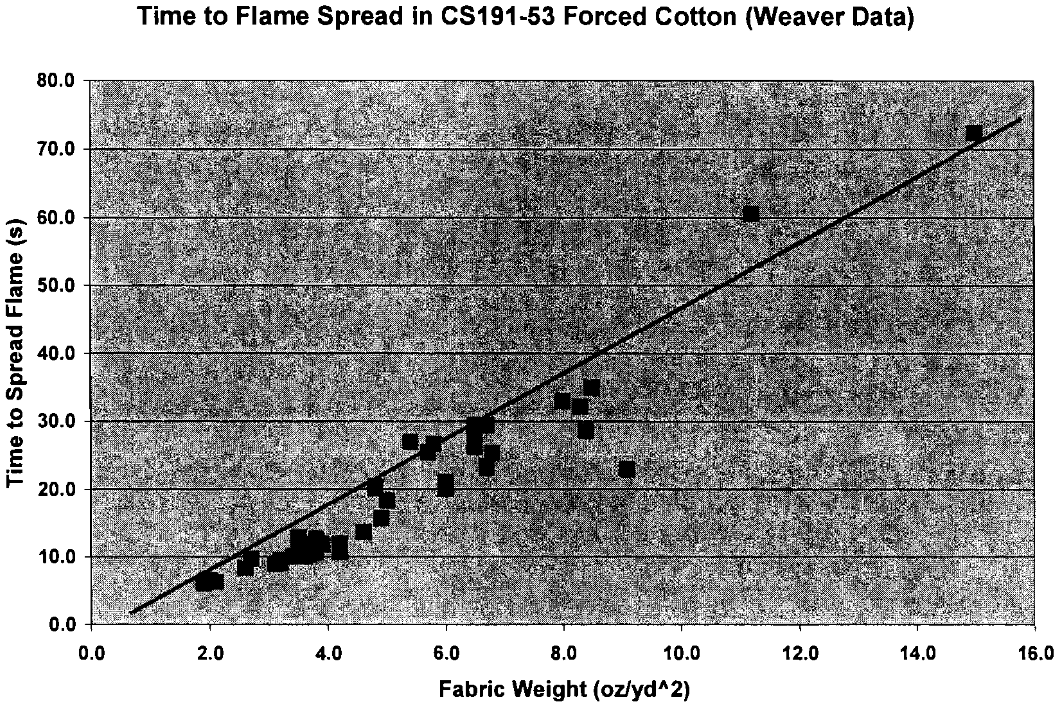

Figure 12: Weaver [6] time to flame spread data for cotton fabrics plotted against fabric weight.

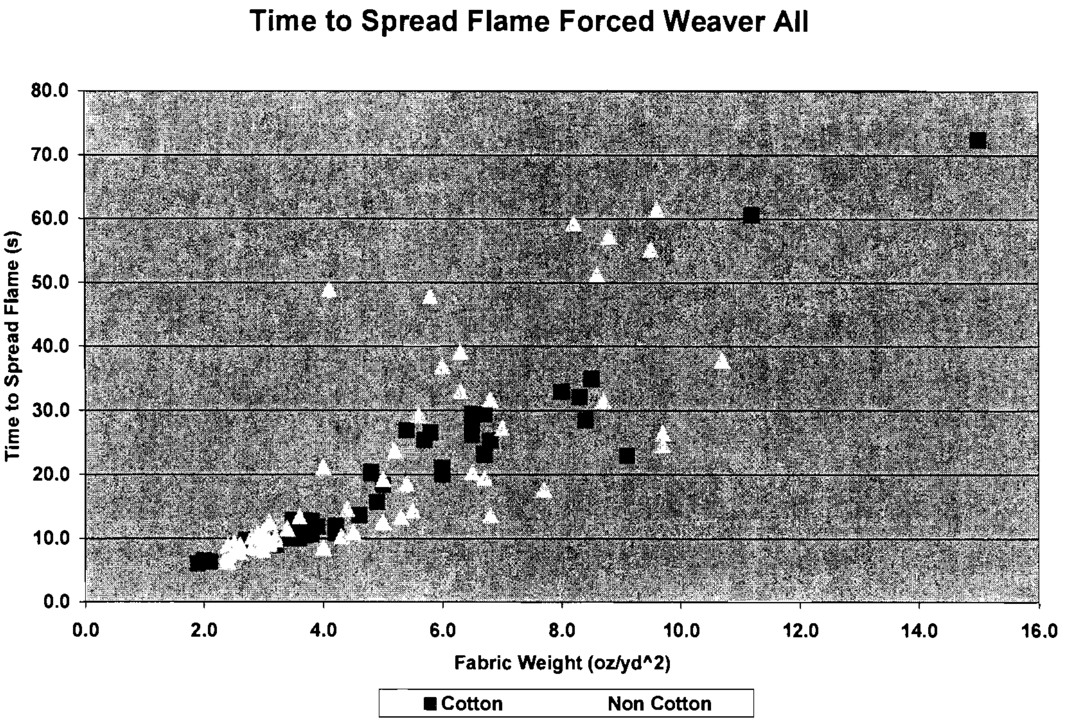

Figure 13: Weaver [6] time to flame spread data for cotton and non cotton fabrics plotted against fabric weight.

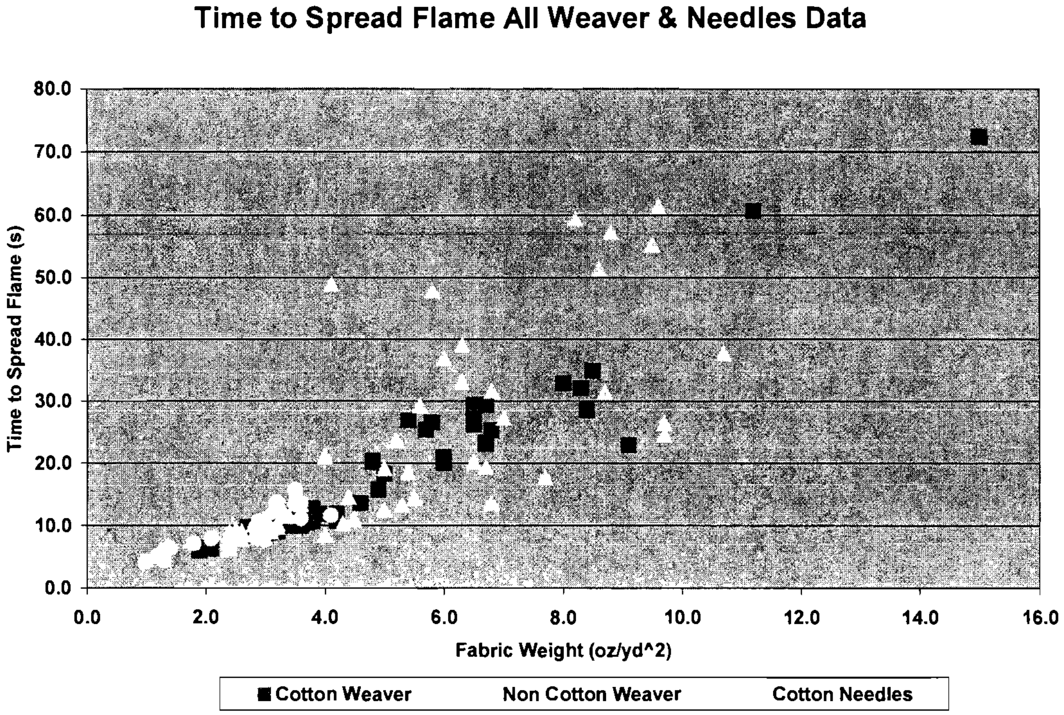

Figure 14: Data from Figures 11 and 13 plotted together

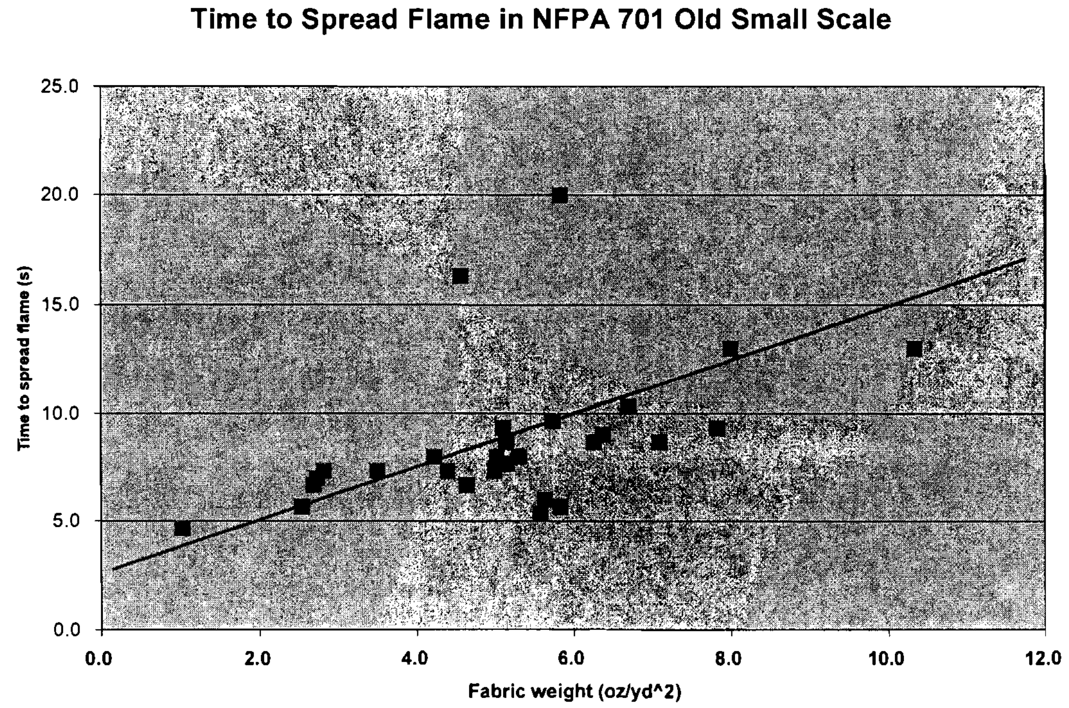

Figure 15: Hirschler [19] time to flame spread data for a small scale NFPA 701-1989 vertical test plotted against fabric weight.

The analysis presented of the 3 different tests conducted provided a 'real scale check' of the test results based on the 16CFR1610 test and the ad-hoc candle vertical burn test compared to the mannequin test. Tables 2 and 4 show that it appears that all 3 tests provided similar flame spread data within a reasonable amount of deviation. Furthermore, times required for forced ignition also appear to be fairly consistent.

There does not appear to be an easy way to illustrate a single direct correlation that addresses all the fabrics used. This is, in particular due to the inherent effects of fabric composition whereby the tested materials included thermoplastics, cellulosics and blends.

TABLE 4 - Ranking of Garments Based on Five Different Criteria: Four Types of Fire Test Results and Fabric Areal Density

			Areal Density	16CFR1610		Vertical Ignition	Mannequin test *
Item #	Type of Garment	Density (g/m^2)		Time for flame to spread 5 in	Time Needed for Forced Ignition	Overall	Overall
A-1	Scarf	33	17	15	12	7	N/A
A-2	Scarf	46	16	15	12	17	N/A
B-1	Sun Dress	81	15	14	17	15	5
A-3	Blouse	106	14	12	9	16	N/A
B-2	Dress Lining	116	13	10	12	13	4
B-3	Sleeved Dress	141	12	15	12	13	8
B-4	Nightgown	169	11	12	7	10	6
B-5	Party Dress	176	10	11	10	11	7
A-4	Dress	215	9	9	12	2	N/A
A-5	Blouse	235	8	7	7	4	N/A
B-6	Sleeveless Dress	247	5	1	7	1	1
A-6	Trousers	256	5	6	4	12	N/A
A-7	Top/Tee Shirt	258	5	1	4	6	NA/
A-8	Skirt	302	4	5	4	9	N/A
B-7	Skirt	324	3	7	3	8	3
B-8	Dress	419	2	4	1	5	2
A-9	Jeans	466	1	3	2	3	N/A

* Note that only B series garments were tested on the Mannequin

CONCLUSIONS

The testing was planned to search for possible correlations between fabric test modes, fabric composition and fire related properties. From the empirical data recorded, it appears that the three test exposures utilized were reasonably consistent in providing indications regarding the fire performance of the fabrics tested. As such, the general trend shown demonstrated that, as areal density (weight) of fabrics increase, their times to forced ignition and their times to spread flame across their surface to the top of a vertical sample both also increase, leading to improved fire performance. The most important consequence of this observation is that better fire performance in heavier fabrics is largely, *but not completely*, independent of fabric composition.

In view of the results observed for the variety of fabrics evaluated here, the hazard to an individual wearing a garment composed of a specific fabric type is far more complex an issue than can be simply assessed based on whether fabric composition is of a thermoplastic material, a charring material or a blend.

In terms of the regulatory implications it appears that the regulation of very light weight fabrics should be an important consideration for most chemical compositions (with a few exceptions) and that the cut off value of 2.6 oz/yd^2 may be relatively arbitrary.

REFERENCES

1. Rohr, K.D., "Products First Ignited in US Home Fires", NFPA (National Fire Protection Association) Fire Analysis & Research Division, Quincy, MA, April 2005.
2. 16CFR1610, Title 16, Commercial Practices, Chapter II, Consumer Product Safety Commission, Part 1610, "Standard for the Flammability of Clothing Textiles", Flammable Fabrics Act Regulations, US Federal Government.
3. Needles, H.L., "Textile Flammability Standards and Clothing Fires, " in Proc. of the Eighteenth Int'l Conf on Fire Safety, Ed. C.J., Hilado, Millbrae, CA, pp 188-89 (1993).
4. LeBlanc, R. Bruce, "Of Shoes and Ships and Sealing Wax – of Cabbages and Kings or Of Consumer Products and Government Regulation" in Proc. of the 1978 Symposium on Textile Flammability, LeBlanc Research Corp., East Greenwich, RI, (1978).
5. LeBlanc, R. Bruce, "Flammability and Fire Resistance of Textiles" Proc. Of the Am. Assoc. of Textile Chemists and Colorists/American Dyestuff Reporter, Dec 30 issue, pp 35-38 (1963).
6. Weaver, J.W., "Rate of burning of Apparel Fabrics," J. Textile Chemist and Colorist, 8(11) pp 46- 51 (1976).
7. Howry, K and Baker, C.A., "25 Years of Flammability Rules" Modern Textiles, Part I (April, p. 19), Part II (May, p. 46), Part III (July, p. 34), and Part IV (August., p. 22) (1978).

8. Anderson, J.J., "Flame Resistant Clothing and the American Consumer," Bobbin, March issue pp. 78-91 (1986).
9. Culp, L., "When Products are Flammable, is Labeling Required?" Texas Bar Journal, (June) p. 584-587 (1988).
10. Cullis, C.F., and Hirschler, M.M., "The Combustion of Organic Polymers", Oxford University Press, Oxford, UK, 1981.
11. 16CFR1615, Title 16, Commercial Practices, Chapter II, Consumer Product Safety Commission, Part 1615, "Standard for the Flammability of Children's Sleepwear: Sizes 0 through 6X (FF 3-71)", Flammable Fabrics Act Regulations, US Federal Government.
12. Miller, Allison and Karter, Michael, "U.S. Home Fire Deaths: The old and very young at highest risk," NFPA Member Newsletter, April/May Issue 776, pp 1 (1990).
13. Fahy, R.F., 1993. "Leaving Children Unsupervised in Playing with Fire," NFPA Fire Journal, May/June ed'n, pp. 54-58 (1993).
14. Hirschler, M.M., (Editor-in-chief), and Debanne, S.B., Larsen, J.B., and Nelson, G.L., "Carbon Monoxide and Human Lethality - Fire and Non-Fire Studies", Elsevier, London, UK, 1993.
15. Hall, J., "Patterns of Fire Casualties in Home Fires by Age and Sex", NFPA (National Fire Protection Association) Fire Analysis & Research Division, Quincy, MA (2001).
16. Hall, J., "Children Playing with Fire", NFPA (National Fire Protection Association) Fire Analysis & Research Division, Quincy, MA, March 2005.
17. Hall, J., "Characteristics of Home Fire Victims", (National Fire Protection Association) Fire Analysis & Research Division, Quincy, MA, July 2005.
18. Needles, H.L., "Current Issues in Clothing Flammability: Testing and Regulation", 16th. Int. Conf. Fire Safety, Ed. C.J. Hilado, Product Safety Corp., San Francisco, CA, pp. 175-77 (1991).
19. Hirschler, M.M. and Piansay, T., "Fabric Flammability: Survey of Flame Spread of Modern Fabrics", Business Communications Company Seventh Ann. Conference on Recent Advances in Flame Retardancy of Polymeric Materials, May 20-22, 1996, Stamford, CT, Ed. M. Lewin, pp. 263-274, Norwalk, CT, 1996.
20. NFPA 701, "Standard Methods of Fire Tests for Flame-Resistant Textiles and Films - 1989 Edition", NFPA (National Fire Protection Association), Quincy, MA, 1989 (This test is no longer contained in later editions of NFPA 701).

ATTACHMENT 6

Furniture Manufacturers Complying with UFAC - April 2008

Albert Hugo Assoc. Inc., Jacksonville, FL
Alexvale/Kincaid, Taylorsville, NC
American Furniture, Pontotoc, MS
American Leather Inc., Dallas, TX
American of Martinsville, Martinsville, VA
Ashley Furniture, Arcadia, WI
AW Manufacturing, Shannon, MS
Baker, Knapp & Tubbs, High Point, NC
Barcalounger Company, Rocky Mount, NC
Barn Door Furniture, Henderson, NC
Bassett Upholstery Co., Newton, NC
Bauhaus USA, Inc., Saltillo, MS
Beachley Furniture Co. Inc., Hagerstown, MD
Bench Craft, Blue Mountain, MS
Berkline Corporation, Morristown, TN
Bernhardt Industries, Lenoir, NC
Best Chairs Inc., Ferdinand, IN
Bradington Young, Cherryville, NC
Broyhill Furniture Industries, Lenoir, NC
C.R. Laine Furniture Company, Hickory, NC
CaliaItalia, SPA, Matera, Italy
Capris Furniture, Ocala, FL
Carlton Manufacturing Inc., Elkhart, IN
Carlton Manufacturing Inc., Ocala, Fl
Carlton Manufacturing Inc., Mount Vernon, TX
Carolina Business Furniture, Archdale, NC
Carson's Inc., Archdale, NC
Caye Upholstery, New Albany, MS
Century Furniture, Hickory, NC
Chromcraft Corporation, Senatobia, MS
Classic Gallery, High Point, NC
Clayton Marcus Company, Inc., Hickory, NC
Cleveland Chair Co, Cleveland, TN
Cochrane Furniture Co., Lincolnton, NC
Council Companies, Denton, NC
Craftmaster Furniture, Taylorsville, NC
DeCheng Furniture, China
Drexel Heritage, Hickory, NC
Elite Leather Co., Chino, CA
England, New Tazewell, TN
Ethan Allen, Danbury, CT
Fairfield Chair Co., Lenoir, NC
Flexsteel Industries, Inc., Dubuque, IA
Flexsteel Industries, Inc., Riverside, CA
Franklin Corporation, Houston, MS
Futuristic Inc., Bean Station, TN
Golden Chair, Houlka, MS
Greene Bros. Furniture Co., N. Wilkesboro, NC
H.M. Richards, Baldwyn, MS
HTL Furniture, China
Haining Mengnu Group, China
Haining Nice Harvest Furniture, China
Harden Furniture Co., McConnellsville, NY
Henredon Upholstery, High Point, NC
Hickory Chair Company, Hickory, NC
Hickory Hill Furniture Company, Fulton, MS
Homecrest Industries, Wadena, MS
Hua Tong Industries, China
ItalSofa, Salvador, Brazil
ItalSofa, Shanghai, China
Jackson Mfg. Co., Cleveland, TN
Karges Furniture Co. Inc., Evansville, IN
Kevin Charles, Tamarac, FL
Key City Furniture Co., Wilkesboro, NC
King Hickory Furniture Co., Hickory, NC
Kisabeth Co. Inc., Ft. Worth, TX
Klaussner Corp., Milford, IA
Klaussner Furniture Ind., Inc., Asheboro, NC
Klote International Corp., Maryville, TN
Kroehler Furniture Inds., Conover, NC
L. Powell Company, Culver City, CA
La-Z-Boy Inc., Monroe, MI
Lancer, Inc., Star, NC
Lane Furniture, Tupelo, MS
Laneventure, Conover, NC
Leathercraft, Inc., Conover, NC
Leather Trend, San Diego, CA
Lexington Home Brands, Hildebran, NC
Max Home, Fulton, MS
Mayo Manufacturing Corp., Texarkana, TX
Meadowbrook Furniture, Hickory Flat, MS
Med-Lift & Mobility, Inc., Calhoun City, MS
Modern Of Marshfield, Inc., Marshfield, WI
Natuzzi, Santeramo, Italy
New Generations Furniture, McKenzie, TN
Norwalk Furniture Corp., Norwalk, OH
OFS/Styline Industries, Huntingburg, IN
Overnight Sofa Corporation, Hickory, NC
Pearson Furniture Co., High Point, NC
Peoploungers, Inc., Nettleton, MS
Providence House Furniture, Maiden, NC
Riverrside Furniture, Ft.. Smith, AR
Rowe Furniture Corp., Elliston, VA
Sam Moore Furniture Inds., Inc Bedford, VA
Schnadig Corporation, Belmont, MS
Sherrill Furniture Company, Hickory, NC
Skyline Furniture, Thornton, IL
Smith Bros. Of Berne, Inc., Berne, IN
Southern Furniture Company, Conover, NC
Southern Motion, Inc., Pontotoc, MS
Southwood Furniture Corp., Hickory, NC
St. Timothy Chair, Hickory, NC
Stanford Furniture Corporation, Claremont, NC
Style Upholstering Inc., Hickory, NC
Superb Creation, Hong Kong
T.L. Bayne Co., Inc., Harlan, KY
TRS Furniture Co., Thomasville, NC
Thayer Coggin, Inc., High Point, NC
Thomasville Furniture, Thomasville, NC
Thomasville Upholstery, Hickory, NC
Tomlinson Furniture, Thomasville, NC
True Seating Concepts, Irvine, CA
University Loft, Morristown, TN
Vanguard Furniture Co., Inc. Hickory, NC
Wanvog Furniture, China
Woodmark Originals, Inc., High Point
Yu-Wei Company, China

UFAC℠

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RETAILERS: >> UFAC HONOR ROLL OF RETAILERS

Alabama

La-Z-Boy Furniture Galleries, Birmingham
La-Z-Boy Furniture Galleries, Dothan
La-Z-Boy Furniture Galleries, Huntsville
La-Z-Boy Furniture Galleries, Irondale
La-Z-Boy Furniture Galleries, Mobile
La-Z-Boy Furniture Galleries, Montgomery
Spiller Furniture, Tuscaloosa
Wood Lane, Northport

Alaska

La-Z-Boy Furniture Galleries, Anchorage
Sadler's Home Furnishings, Anchorage

Arizona

Breuners Arizona, Scottsdale
La-Z-Boy Furniture Galleries, Glendale
La-Z-Boy Furniture Galleries, Glendale
La-Z-Boy Furniture Galleries, Mesa
La-Z-Boy Furniture Galleries, Mesa
La-Z-Boy Furniture Galleries, Phoenix
La-Z-Boy Furniture Galleries, Scottsdale
La-Z-Boy Furniture Galleries, Tempe
La-Z-Boy Furniture Galleries, Tucson
La-Z-Boy Furniture Galleries, Tucson

Arkansas

Brandon House Furniture, Little Rock
La-Z-Boy Furniture Galleries, Little Rock

California

Fedde Furniture, Pasadena
Hanford Furniture, Hanford
Jerome's Furniture, San Diego
Lawrance Contemporary, San Diego
La-Z-Boy Furniture Galleries, Anaheim

Minnesota

Gabbert's Furniture, Minneapolis
Slumberland, Little Canada

Mississippi

Aycock-Roberts Furniture, Hittiesburg
La-Z-Boy Furniture Galleries, Gulfport erkins
Furniture, Brookhaven

Missouri

La-Z-Boy Furniture Galleries, Hazelwood
La-Z-Boy Furniture Galleries, Independence
La-Z-Boy Furniture Galleries, Manchester
La-Z-Boy Furniture Galleries, Springfield
La-Z-Boy Furniture Galleries, St. Louis
Rust & Martin, Cape Girardeau

Montana

La-Z-Boy Furniture Galleries, Billings

Nebraska

Nebraska Furniture Mart, Omaha

Nevada

Carson Furniture, Carson City
Garrett's Fine Furniture, Las Vegas

New Hampshire

La-Z-Boy Furniture Galleries, Manchester

New Jersey

Huffmann Koos, River Edge
La-Z-Boy Furniture Galleries, Cedar Grove

La-Z-Boy Furniture Galleries, Cerritos
La-Z-Boy Furniture Galleries, Chico
La-Z-Boy Furniture Galleries, Chula Vista
La-Z-Boy Furniture Galleries, Corte Madera
La-Z-Boy Furniture Galleries, Costa Mesa
La-Z-Boy Furniture Galleries, El Cajon
La-Z-Boy Furniture Galleries, Fresno
La-Z-Boy Furniture Galleries, Hemet
La-Z-Boy Furniture Galleries, Irvine
La-Z-Boy Furniture Galleries, Lake Forest
La-Z-Boy Furniture Galleries, Northridge
La-Z-Boy Furniture Galleries, Oxnard
La-Z-Boy Furniture Galleries, Pleasant Hill
La-Z-Boy Furniture Galleries, Pleasanton
La-Z-Boy Furniture Galleries, Ranch, Cordova
La-Z-Boy Furniture Galleries, Redding
La-Z-Boy Furniture Galleries, Riverside
La-Z-Boy Furniture Galleries, Roseville
La-Z-Boy Furniture Galleries, Sacramento
La-Z-Boy Furniture Galleries, Sacramento
La-Z-Boy Furniture Galleries, Salinas
La-Z-Boy Furniture Galleries, San Bernardino
La-Z-Boy Furniture Galleries, San Diego
La-Z-Boy Furniture Galleries, S. San Francsico
La-Z-Boy Furniture Galleries, San Jose
La-Z-Boy Furniture Galleries, San Marcos
La-Z-Boy Furniture Galleries, Santa Clara
La-Z-Boy Furniture Galleries, Santa Rosa
La-Z-Boy Furniture Galleries, Torrance
La-Z-Boy Furniture Galleries, Ukiah
La-Z-Boy Furniture Galleries, Victor Ville
Russell's Furniture, San Jose
Silverado Furniture, Napa
The Rose Collection, Los Gatos
Valley Manor Furniture, Northridge

Colorado

Kacey Fine Furniture, Denver
La-Z-Boy Furniture Galleries, Colarado Springs
La-Z-Boy Furniture Galleries, Denver
La-Z-Boy Furniture Galleries, Englewood
La-Z-Boy Furniture Galleries, Fort Collins
La-Z-Boy Furniture Galleries, Littleton
La-Z-Boy Furniture Galleries, Westminster

Connecticut

La-Z-Boy Furniture Galleries, Brookfield
La-Z-Boy Furniture Galleries, Clinton
La-Z-Boy Furniture Galleries, Orange
La-Z-Boy Furniture Galleries, Waterbury
Wayside Furniture, Milford
Wilson Furniture, Wallingford

Delaware

La-Z-Boy Furniture Galleries, Newark
La-Z-Boy Furniture Galleries, Wilmington

Florida

Baer's Furniture, Pompano Beach
El Dorado Furniture, Miami Gardens

La-Z-Boy Furniture Galleries, Maple Shade
La-Z-Boy Furniture Galleries, Metuchen
La-Z-Boy Furniture Galleries, Springfield
Llyod's Furniture, Somerville
Mart Furniture Galleries, Middletown
Whippany Manor's Ethan Allen, Whippany

New Mexico

La-Z-Boy Furniture Galleries, Albuquerque
La-Z-Boy Furniture Galleries, Albuquerque

New York

Bayles Furniture, Inc., Rochester
La-Z-Boy Furniture Galleries, Amherst
La-Z-Boy Furniture Galleries, Carle Place
La-Z-Boy Furniture Galleries, Clay
La-Z-Boy Furniture Galleries, Farmingdale
La-Z-Boy Furniture Galleries, Latham
La-Z-Boy Furniture Galleries, Orchard Park
La-Z-Boy Furniture Galleries, Rochester
La-Z-Boy Furniture Galleries, Rockville Center
Loomis Barn, Rushville
Raymour & Flanigan, Liverpool
Seaman Furniture, Uniondale
La-Z-Boy Furniture Galleries, Henderson
La-Z-Boy Furniture Galleries, Las Vegas
La-Z-Boy Furniture Galleries, Las Vegas
La-Z-Boy Furniture Galleries, Reno
Winans Furniture, Inc., Carson City

North Carolina

Expressions Custom Furniture, Hickory
La-Z-Boy Furniture Galleries, Charlotte
La-Z-Boy Furniture Galleries, Greensboro
La-Z-Boy Furniture Galleries, Pineville
La-Z-Boy Furniture Galleries, Raleigh
La-Z-Boy Furniture Galleries, Winston-Salem
Rose Furniture, High Point
Sutton Council Furniture, Wilmington
Utility Craft, High Point
Wood-Armfield, High Point

Ohio

La-Z-Boy Furniture Galleries, Akron
La-Z-Boy Furniture Galleries, Akron
La-Z-Boy Furniture Galleries, Boardman
La-Z-Boy Furniture Galleries, Cincinnati
La-Z-Boy Furniture Galleries, Cincinnati
La-Z-Boy Furniture Galleries, Columbus
La-Z-Boy Furniture Galleries, Columbus
La-Z-Boy Furniture Galleries, Dayton
La-Z-Boy Furniture Galleries, Hilliard
La-Z-Boy Furniture Galleries, Huber Heights
La-Z-Boy Furniture Galleries, Lima
La-Z-Boy Furniture Galleries, Loveland
La-Z-Boy Furniture Galleries, Lyndhurst
La-Z-Boy Furniture Galleries, Maumee
La-Z-Boy Furniture Galleries, Middleburgh Heights
La-Z-Boy Furniture Galleries, Niles

Halpern's Ethan Allen, Miami
Harrison Furniture CO, Clearwater
La-Z-Boy Furniture Galleries, Boca Raton
La-Z-Boy Furniture Galleries, Bradenton
La-Z-Boy Furniture Galleries, Ft. Meyers
La-Z-Boy Furniture Galleries, Ft. Lauderdale
La-Z-Boy Furniture Galleries, Gainesville
La-Z-Boy Furniture Galleries, Jacksonville
La-Z-Boy Furniture Galleries, Lake Worth
La-Z-Boy Furniture Galleries, Largo
La-Z-Boy Furniture Galleries, Maitland
La-Z-Boy Furniture Galleries, Melbourne
La-Z-Boy Furniture Galleries, Naples
La-Z-Boy Furniture Galleries, New Port Richey
La-Z-Boy Furniture Galleries, Orange Park
La-Z-Boy Furniture Galleries, Orlando
La-Z-Boy Furniture Galleries, Orlando
La-Z-Boy Furniture Galleries, Palm Harbor
La-Z-Boy Furniture Galleries, Panama City
La-Z-Boy Furniture Galleries, Pembroke Pines
La-Z-Boy Furniture Galleries, Pensacola
La-Z-Boy Furniture Galleries, Sarasota
La-Z-Boy Furniture Galleries, Sunrise
La-Z-Boy Furniture Galleries, Tampa
La-Z-Boy Furniture Galleries, Tampa
La-Z-Boy Furniture Galleries, West Palm Beach
Robb & Stucky, Ft. Myers
Thomasville Home Furnishings, Altamonte Springs

Georgia

Beverly Hall Furniture Galleries, Atlanta
La-Z-Boy Furniture Galleries, Atlanta
La-Z-Boy Furniture Galleries, Augusta
La-Z-Boy Furniture Galleries, Douglasville
La-Z-Boy Furniture Galleries, Kennesaw
La-Z-Boy Furniture Galleries, Lawrenceville
La-Z-Boy Furniture Galleries, Macon
La-Z-Boy Furniture Galleries, Morrow
La-Z-Boy Furniture Galleries, Roswell
La-Z-Boy Furniture Galleries, Savannah

Hawaii

La-Z-Boy Furniture Galleries, Aiea

Idaho

Ennis Furniture, Boise
La-Z-Boy Furniture Galleries, Boise

Illinois

ATI Carriage House, Lombard
Cohen Furniture, Peoria
Hufford Furniture, Chicago
La-Z-Boy Furniture Galleries, Arlington Heights
La-Z-Boy Furniture Galleries, Aurora
La-Z-Boy Furniture Galleries, Berwyn
La-Z-Boy Furniture Galleries, Champaign
La-Z-Boy Furniture Galleries, Chicago
La-Z-Boy Furniture Galleries, Elmhurst
La-Z-Boy Furniture Galleries, Fairview Heights

La-Z-Boy Furniture Galleries, North Olmstead
La-Z-Boy Furniture Galleries, Northwood
La-Z-Boy Furniture Galleries, Toledo
La-Z-Boy Furniture Galleries, Zanesville
White's Fine Furniture, Columbus

Oregon

Blackledge Furniture, Corvallis
La-Z-Boy Furniture Galleries, Beaverton
La-Z-Boy Furniture Galleries, Bend
La-Z-Boy Furniture Galleries, Eugene
La-Z-Boy Furniture Galleries, Portland
La-Z-Boy Furniture Galleries, Portland
La-Z-Boy Furniture Galleries, Salem
La-Z-Boy Furniture Galleries, Tualatin

Pennsylvania

Arnold's, Lancaster
Chertok's Furniture, Coatesville
D & D Home Furnishings, Whitehall
Galbraith's R & D Furniture, Brookville
Good's Furniture, Lancaster
Interiors 2000, Lancaster
Izzy Miller Furniture, Carnegie
John V. Schultz, Erie
Kweller's Georgetown Manor, Allentown
La-Z-Boy Furniture Galleries, Lancaster
La-Z-Boy Furniture Galleries, McMurray
La-Z-Boy Furniture Galleries, Monroeville
La-Z-Boy Furniture Galleries, Montgomery Ville
La-Z-Boy Furniture Galleries, Pittsburgh
La-Z-Boy Furniture Galleries, Scranton
La-Z-Boy Furniture Galleries, Shillington
La-Z-Boy Furniture Galleries, Springfield
La-Z-Boy Furniture Galleries, Whitehall
La-Z-Boy Furniture Galleries, Wilkes Barre
Lush Brothers, State College
Mared Ethan Allen, Pittsburgh
Nathan's, Hazelton
Oskar Huber Furniture & Design, Southampton
Silver Furniture, Lansford
Today's Home, Pittsburgh
Wolf Furniture Enterprises, Altoona
Your Living Room, Lemoyne

Rhode Island

La-Z-Boy Furniture Galleries, Warwick

South Carolina

La-Z-Boy Furniture Galleries, Columbia
La-Z-Boy Furniture Galleries, Greenville
La-Z-Boy Furniture Galleries, N. Charleston
La-Z-Boy Furniture Galleries, Spartanburg
Maynard's of Belton, Belton
Prosperity Furniture Company, Prosperity
Southeastern Galleries, Charleston

Tennessee

La-Z-Boy Furniture Galleries, Joliet
La-Z-Boy Furniture Galleries, Lisle
La-Z-Boy Furniture Galleries, Morton Grove
La-Z-Boy Furniture Galleries, Oaklown
La-Z-Boy Furniture Galleries, Orland Park
La-Z-Boy Furniture Galleries, Rockford
La-Z-Boy Furniture Galleries, Schaumburg
La-Z-Boy Furniture Galleries, Springfield
La-Z-Boy Furniture Galleries, Vernon Hills
La-Z-Boy Furniture Galleries, Waukegan
Plunkett Furniture, Skokie
Wickes, Wheeling

Indiana

Kittle's, Indianapolis
La-Z-Boy Furniture Galleries, Evansville
La-Z-Boy Furniture Galleries, Fort Wayne
La-Z-Boy Furniture Galleries, Indianapolis
La-Z-Boy Furniture Galleries, Indianapolis
La-Z-Boy Furniture Galleries, Indianapolis
La-Z-Boy Furniture Galleries, Merrillville
La-Z-Boy Furniture Galleries, South Bend
La-Z-Boy Furniture Galleries, Terre Haute
Ries Furniture Company, South Bend
Tilles Interiors, Monster

Kansas

La-Z-Boy Furniture Galleries, Florence
La-Z-Boy Furniture Galleries, Lexington
La-Z-Boy Furniture Galleries, Louisville
Keller Furniture Galleries, Hays

Lousiana

Compass Furniture, Jefferson
La-Z-Boy Furniture Galleries, Baton Rouge
La-Z-Boy Furniture Galleries, Harvey
La-Z-Boy Furniture Galleries, Lafayette
La-Z-Boy Furniture Galleries, Metairie

Maine

La-Z-Boy Furniture Galleries, Scarborough
Young's Furniture, Portland

Maryland

Garon's Ethan Allen, Baltimore
La-Z-Boy Furniture Galleries, Annapolis
La-Z-Boy Furniture Galleries, Bel-Air
La-Z-Boy Furniture Galleries, Essex
La-Z-Boy Furniture Galleries, Glen Burnie
La-Z-Boy Furniture Galleries, Laurel
La-Z-Boy Furniture Galleries, Rockville
La-Z-Boy Furniture Galleries, Towson
Mastercraft Interiors, Beltsville

Massachusetts

Alpert's Seekonk
Bradford Furniture, Littleton

La-Z-Boy Furniture Galleries, Antioch
La-Z-Boy Furniture Galleries, Chattanooga
La-Z-Boy Furniture Galleries, Knoxville
La-Z-Boy Furniture Galleries, Memphis
Sprintz Furniture, Nashville

Texas

Adele Hunt Furniture, Dallas
Finger Furniture, Houston
Lack's Stores, Victoria
La-Z-Boy Furniture Galleries, Amarillo
La-Z-Boy Furniture Galleries, Arlington
La-Z-Boy Furniture Galleries, Austin
La-Z-Boy Furniture Galleries, Dallas
La-Z-Boy Furniture Galleries, El Paso
La-Z-Boy Furniture Galleries, Houston
La-Z-Boy Furniture Galleries, Houston
La-Z-Boy Furniture Galleries, Lewisville
La-Z-Boy Furniture Galleries, Lubbock
La-Z-Boy Furniture Galleries, Mesquite
La-Z-Boy Furniture Galleries, N. Richland Hills
La-Z-Boy Furniture Galleries, Plano
La-Z-Boy Furniture Galleries, San Antonio
La-Z-Boy Furniture Galleries, San Antonio
La-Z-Boy Furniture Galleries, Webster
Louis Shanks of Texas, Austin
Spears, Lubbock
Star Furniture, Houston

Utah

R.C. Willey, Salt Lake City

Vermont

Rutland House, Rutland

Virginia

Grand Piano & Furniture, Roanoke
La-Z-Boy Furniture Galleries, Chesapeake
La-Z-Boy Furniture Galleries, Fairfax
La-Z-Boy Furniture Galleries, Fredericksburg
La-Z-Boy Furniture Galleries, Hampton
La-Z-Boy Furniture Galleries, Richmond
La-Z-Boy Furniture Galleries, Richmond
La-Z-Boy Furniture Galleries, Springfield
La-Z-Boy Furniture Galleries, Virginia Beach
La-Z-Boy Furniture Galleries, Woodbridge
Schewels Furniture, Lynchburg
Williams Wayside Furniture, Springfield
Willis Furniture, Virginia Beach

Washington

Davis Furniture, Wenatchee
La-Z-Boy Furniture Galleries, Bremerton
La-Z-Boy Furniture Galleries, Lynnwood
La-Z-Boy Furniture Galleries, Spokane
La-Z-Boy Furniture Galleries, Spokane
La-Z-Boy Furniture Galleries, Tacoma

La-Z-Boy Furniture Galleries, Burlington
La-Z-Boy Furniture Galleries, Hanover
La-Z-Boy Furniture Galleries, Hyannis
La-Z-Boy Furniture Galleries, N. Dartmouth
La-Z-Boy Furniture Galleries, Saugas
Jordan's Furniture, Avon
Rotman's Furniture, Worcester

Michigan

Art Sample Furniture, Saginaw
Art Van Furniture, Warren
Classic Interiors, Livonia
Englander's Other Place, Ferndale
Gardner-White, Warren
Gorman's, Southfield
Great Lakes Interiors, Holland
Jonathan Stevens, Grand Rapids
Klingman Furniture, Grand Rapids
La-Z-Boy Furniture Galleries, Ann Arbor
La-Z-Boy Furniture Galleries, Canton
La-Z-Boy Furniture Galleries, Flint
La-Z-Boy Furniture Galleries, Grand Rapids
La-Z-Boy Furniture Galleries, Lansing
La-Z-Boy Furniture Galleries, Novi
La-Z-Boy Furniture Galleries, Portage
La-Z-Boy Furniture Galleries, Saginaw
La-Z-Boy Furniture Galleries, Sterling Heights
La-Z-Boy Furniture Galleries, Taylor
La-Z-Boy Furniture Galleries, Warren
Markey-Elliott, Inc., Saginaw
Oscar Rau, Frankenmuth
Pioneer Furniture, Sterling Heights
Schwark Furniture, Shelby
Skaff Furniture, Flint
Tri-City Furniture, Auburn
Van Hill Furniture, Zeeland

La-Z-Boy Furniture Galleries, Tukwila
Masin's Furniture, Seattle

West Virginia

La-Z-Boy Furniture Galleries, Barboursville
La-Z-Boy Furniture Galleries, South Charleston
La-Z-Boy Furniture Galleries, Vienna

Wisconsin

Carriage House of Brookfield, Menomonee Falls
La-Z-Boy Furniture Galleries, Brookfield
La-Z-Boy Furniture Galleries, Greenfield
La-Z-Boy Furniture Galleries, Madison
Steinhafel's, New Berlin

Canada

La-Z-Boy Furniture Galleries, Burlington
La-Z-Boy Furniture Galleries, Calgary
La-Z-Boy Furniture Galleries, Edmonton
La-Z-Boy Furniture Galleries, Nepean
La-Z-Boy Furniture Galleries, Oshawa
La-Z-Boy Furniture Galleries, Victoria
La-Z-Boy Furniture Galleries, Winnipeg

International Companies

Casa Italy Furnishings House, Singapore
La-Z-Boy Furniture Galleries, Madrid/Spain

ATTACHMENT 7

Fire Safety Journal **18** (1992) 255–272

Heat Release Rate: The Single Most Important Variable in Fire Hazard*

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ABSTRACT

Heat release rate measurements are sometimes seen by manufacturers and product users as just another piece of data to gather. It is the purpose of this paper to explain why heat release rate is, in fact, the single most important variable in characterizing the 'flammability' of products and their consequent fire hazard. Examples of typical fire histories are given which illustrate that even though fire deaths are primarily caused by toxic gases, the heat release rate is the best predictor of fire hazard. Conversely, the relative toxicity of the combustion gases plays a smaller role. The delays in ignition time, as measured by various Bunsen burner type tests, also have only a minor effect on the development of fire hazard.

INTRODUCTION

The 1988 edition of the compilation of fire tests[1] by the American Society for Testing and Materials (ASTM) alone lists some 77 tests. ASTM is only one of many US and international organizations publishing fire test standards; thus, the actual number of fire tests in use is at least in the hundreds.[2] It is customary to divide the actual fire test standards into two broad categories: (1) reaction-to-fire, or flammability, and (2) fire endurance, or fire resistance.

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* This paper is a contribution of the National Institute of Standards and Technology and is not subject to copyright.

The paper is based on a talk presented at the 1990 Fall meeting of the Fire Retardant Chemical Association, Ponte Vedra Beach, Florida.

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Reaction-to-fire is how a material or product responds to heating or to a fire. This includes ignitability, flame spread, heat release, and the production of various—toxic, obscuring, corrosive, etc., products of combustion. Reaction-to-fire largely concerns the emission of undesired things, e.g. how much heat is emitted, how much smoke, or how fast does the first emission start (ignitability). A reaction-to-fire test is typically performed on *combustibles.*

Fire endurance, by contrast, asks the questions: how well does a product prevent the spread of fire beyond the confines of the room? And, how well does it continue to bear load during the fire? Such a test is performed on *barriers to fire* and *load-bearing elements,* such as walls, floors, ceilings, doors, windows and related items.

The scope of the present paper is restricted to reaction-to-fire tests only.

Manufacturers of resins, fire retardants, and plastic products are accustomed to describing reaction-to-fire performance according to two tests: the UL 94 vertical Bunsen burner test[3] and the limiting oxygen index (LOI) test.[4] The LOI test determines under how low an oxygen fraction a test specimen can continue burning in a candle-like configuration. It has never been correlated to any aspect of full-scale fires. The UL 94 test was developed to determine the resistance to ignition of small plastic parts, such as may be found inside electric switches. For this purpose, it is an accurate simulation of a real fire source. A problem arises when UL 94 data are used, as they often are, to imply how large surfaces or objects made of a particular material might perform. For such situations, when the product is larger than the very small objects envisioned by UL 94, we wish to ask what the proper approach is to evaluating the fire performance.

In this paper, we will provide a brief historical overview of bench-scale reaction-to-fire tests and the relation to hazard in fires. We will then turn to the meaning of heat release in a fire. We will show that although bench-scale heat release rate tests were developed quite early, they could not be put to widespread use without the parallel capability for making heat release rate measurements in full-scale room fires, as a basis for validating the bench-scale tests. We will then provide several examples illustrating the development of fire hazard in full-scale room fires and demonstrate that the heat release rate is, in fact, the most essential variable controlling the rate at which untenable conditions occur. Finally, we will illustrate, by example, the process of combining bench-scale testing and computational techniques to predict successfully the full-scale development of fire hazard.

HISTORICAL BACKGROUND

Early reaction to fire tests

Early reaction-to-fire tests were not developed for general fire protection use. Instead, the development of tests was first done for very narrow, specialized product categories. The earliest standard reaction-to-fire test of which we have a record was for the performance of fire-retarded wood. In 1902, the pioneering Columbia University professor Ira H. Woolson started working with the US Navy to develop a standard test for the burning behavior of fire retardant wood.[5] This test (Fig. 1) was called the 'timber test' and was used for a number of years. Later, additional specialized test methods were devised for that purpose[6] in the 1920s.

The next reaction-to-fire test of which we have a record was from 1905. After a series of disastrous theater fires, the famed American engineer John R. Freeman developed a 'stovepipe' test for flammable fabrics.[7] In this test, strips of test cloth were hung inside a 2-ft-high chimney, and lighted by excelsior kindling at the bottom. Since this was not a readily portable test, he also commissioned the development of an

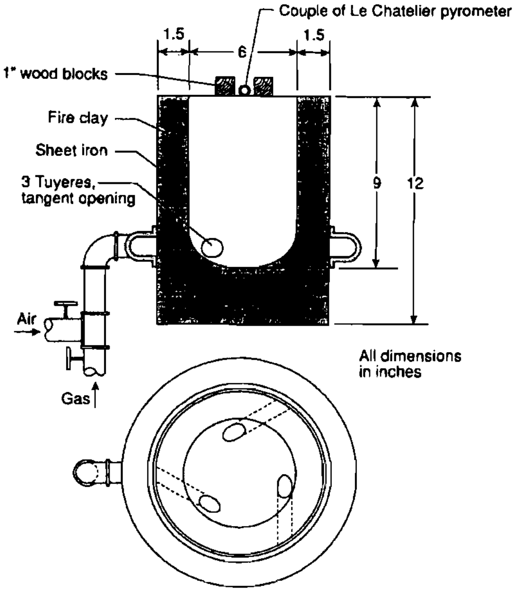

Fig. 1. The first-ever standard reaction-to-fire test method, the 'timber test'.

alcohol-lamp field test. This was known as the Whipple–Fay test, after the names of the two persons hired by Freeman to develop the test. Neither of these became a standard test. The first standard tests for the flammability of textiles arose in England with the alcohol-cup test of the British Standards Institution in 1936,[8] and in the USA with the first version of the current NFPA 701 Bunsen-burner test, proposed by the National Fire Protection Association in 1938.[9]

Flammable fabrics, however, pose a very specialized fire hazard. These can cause injury if they are garments which are ignited on the wearer. In addition, in public spaces, curtains and decorative fabrics can spread fire at a very high speed. Such fires, however, typically burn only a very short time and are not likely to be directly hazardous to those not intimately involved with them. The more serious danger comes from the fact that other combustible materials can be ignited by such textiles. Thus, for materials such as textiles, which are thin and have little combustible mass, the main fire hazard that must be recognized and measured is rapid flame spread. For most other combustibles, the situation, as we shall see, is different.

The need to measure the flammability of additional categories of combustibles was seen during the late 1930s. This resulted in the first Bunsen burner tests for plastics being developed in 1940.[10] In the same period, A. J. Steiner, of Underwriters Laboratories, also developed the Steiner Tunnel Test.[11] This was intended primarily for testing flame spread along cellulosic products, and has since become the main reaction-to-fire test used in US building codes. The method also incorporated a smoke measurement and a 'fuel contributed' measurement, which can be taken to be a crude form of heat release rate. In recent years, this 'fuel contributed' measurement has been deemphasized, and the current ASTM procedure no longer requires that a specific classification be derived from it.[12]

Quantifying hazard in fire

During the 1970s it came to be felt that knowledge about the toxicity of materials was the 'missing link' in understanding fire hazard. Thus, a number of tests were developed and proposed in this area, although none have yet been accepted by US or UK standards organizations or by ISO. Nonetheless, methods for measuring the toxic potency of materials (e.g. the NBS Cup Furnace Method[13]) started being widely used in the 1980s. Yet, the data from them could not be treated in a useful engineering way, since a suitably comprehensive analysis methodology was lacking.

One of the earliest milestones in the search for methods to quantitatively evaluate the fire hazard in buildings was a 2-day workshop on 'Practical Approaches for Smoke Toxicity Hazard Assessment',[14] sponsored by the National Fire Protection Association in February 1984. This workshop convened groups of leading toxicologists, fire protection engineers, fire scientists, fire modelers, and code and fire service representatives to study the problem. Later in 1984, the Toxicity Advisory Committee of NFPA proposed a simple four-step procedure[15] derived from the workshop's efforts. As the project progressed, papers were published which discussed the evolving philosophy and structure of the hazard assessment methodology.[16,17] These papers, and the growing questions regarding combustion product toxicity, stimulated some early hazard analyses using both hand-calculated estimates and some of the available fire models.

In May of 1984, the Toxicity Advisory Committee of the National Fire Protection Association published a procedure for providing 'order of magnitude estimates' of the toxic hazards of smoke for specified situations.[18] In this report, Bukowski based the estimating procedure on a series of algebraic equations, which could be solved on a hand calculator. Individual equations were provided to estimate steady-state values for such parameters as upper layer temperature, smoke density, and toxicity; and graphical solutions were provided for room filling time. This work was followed by the more extensive compilation of such equations for use by the US Navy in assessing fire hazards on ships.[19] Subsequently, the Toxicity Advisory Committee was asked by the National Electrical Code Committee for assistance in addressing a toxicity hazard question regarding polytetrafluoroethylene (PTFE) plenum cables. In providing that help, a hand-calculated analysis was performed.[20] This paper concluded for a single, specified scenario, that the size of room fire needed to cause the decomposition of the cable insulation would itself cause a toxicity hazard in an adjacent space before the cable would become involved.

Several systematized procedures for evaluating the fire hazard in buildings by means of 'hand-crank' computations have been put forth.[21,22] Such computations are simple to perform and can be suitable for estimating. However, the algebraic equations used are limited to steady-state analyses, and cannot deal consistently with the transient aspects of fire behavior. A more complete answer requires a computer to solve the differential equations which describe these transient phenomena. This is the role of computer fire models.

The computer models currently available vary considerably in scope, complexity, and purpose. Simple 'room filling' models such as the

Available Safe Egress Time (ASET) model[23] run quickly on almost any computer, and provide good estimates of a limited number of parameters of interest for a fire in a single compartment. A special purpose model can provide a single function, e.g. COMPF2[24] calculates post-flashover room temperatures. And, very detailed models like the HARVARD V code[25] predict the burning behavior of multiple items in a room, along with the time-dependent conditions therein. In addition to the single-room models mentioned above, there are a smaller number of multi-room models which have been developed. These include the BRI (or Tanaka) transport model[26] which served as a basis for the FAST model included as part of HAZARD I, and the HARVARD VI code[27] a multi-room version of HARVARD V. All of these models are of the zone (or control volume) type. They assume that the buoyancy of the hot gases causes them to stratify into two layers; a hot, smokey upper layer and a cooler lower layer. Experiments have shown this to be a relatively good approximation. While none of these models were written specifically for the purpose of hazard analysis, any of them could be used within the hazard framework to provide required predictions. Their applicability depends upon the problem and the degree of detail needed in the result.

Over the past few years, models began to be used within a hazard analysis framework to address questions of interest. In 1984, Nelson published a 'hazard analysis' of a US Park Service facility which used a combination of models (including ASET) and hand calculations.[28] The calculations were used to determine the impact of various proposed fire protection additions (smoke detectors sprinklers, lighting, and smoke removal) on the number of occupants who could safely exit the building during a specified fire incident.

In 1985, Bukowski conducted a parametric study of the hazard of upholstered furniture using the FAST model.[29] Here, the model was used to explore the impact of changes in the burning properties of furniture items (burning rate, smoke production, heat of combustion, and toxicity) on occupant hazard relative to the random variations of the different houses in which the item might be placed. These latter variables were room dimensions, wall materials, and the effect of closed doors. The conclusion was that reducing the burning rate by a factor of two produced a significantly greater increase in time to hazard than any other variable examined. So much so that the benefit would be seen regardless of any other parameter variation. Results such as this can show a manufacturer where the greatest safety benefit can be achieved for a given investment in redesign of his product.

A more recent example of a hazard analysis application is the elegant work of Emmons on the MGM Grand Hotel fire of 1980. This work, conducted during the litigation of this fire was only recently published.[30] Using the HARVARD V model, Professor Emmons analyzed the relative contributions of the booth seating, ceiling tiles and decorative beams, and the HVAC system, all in the room of origin, on the outcome of the fire. A report issued by the National Academy of Sciences[31] provides two hazard analysis case studies—one making use of the HARVARD V model and the other using experimental data. The cases deal with upholstered furniture and a combustible pipe within a wall, respectively.

It is fairly obvious that one of the first questions a person might wish to ask about the hazard of a building fire is 'How big is the fire?' Thus, it is exceedingly curious, in hindsight, that until fairly recently there was no quantitative way of asking or answering this question. Nowadays, we know that, in quantitative terms, this means, 'Tell me the heat release rate of the fire.' We also know that the heat release rate is measured in kilowatts (kW), or some multiple, e.g. megawatts. We further realize that this is not the same thing as asking what is the flame spread rate of the fire. Thus, neither the E 84 flame spread test nor the Bunsen burner ignitability tests will help us answer this question. It is clear that knowledge of underlying variables related to burning rate is the key to understanding and quantifying the hazard in unwanted fires. Measurement of the heat release rate provides this understanding.

MEASUREMENT OF HEAT RELEASE

Small-scale tests

The fuel-contributed measurement done in E 84 does not qualify as a *measurement* of heat release rate since it is not in the physically correct units of kW. The first apparatus in which heat release rate was measured quantitatively, in correct (albeit, British) units was the FM Construction Materials Calorimeter. It was developed by Thompson and Cousins at the Factory Mutual Research Laboratories in 1959.[32] This was a medium-scale test, with a specimen size of 1·22 by 1·22 m. The method was cumbersome to run and has only been used by the FM system. It is still in use at FM today as part of an approval standard for steel deck roofs.[33]

Progress in heat release rate was still not being made, once the FM test was available, for two reasons: (1) the method was only intended for testing roof decks; and (2) it was a medium-scale test, and there was no room-scale test yet available. If we assume the purpose of a bench-scale test is to reproduce room-scale fire behavior, it becomes clear that little progress in developing bench-scale test methods could be made until heat release rate could be satisfactorily measured in room fires. During the 1970s the small-scale HRR test which came into the widest use was the Ohio State University apparatus (ASTM E 906).[34] This was accompanied by a room fire model[35] which used the bench-scale HRR data to predict large-scale product performance. The OSU HRR apparatus was appealing for its simplicity even though substantial systematic errors accompanied the measurement; thus, it became rather well-known and used in the era prior to when the profession shifted over to using oxygen consumption based methods. The OSU room fire model, however, was based on physics approximations which were not well accepted and, thus, did not play a significant role in hazard quantification.

During the 1970s Parker[36] and Sensenig[37] pioneered the use of oxygen consumption calorimetry as a way of making HRR measurements substantially freer of systematic error. The technique for doing it has been described by Parker[38] and forms the basis for all subsequent HRR measuring apparatuses, both bench-scale and room-scale. As an example, the FMRC Flammability Apparatus[39] was developed using the oxygen consumption technique, but it did not become a standardized HRR test. In fact, during the late 1970s and early 1980s interest in bench-scale HRR testing remained rather small. We now realize that the proper fire hazard assessment role for a bench-scale test is to predict the full-scale fire behavior.[40] However, correlations establishing the successful prediction of the full-scale fire behavior could not be established until adequate capability was available to measure the heat release rate in the full scale.

Having established some of the major historical milestones in this area, we shall examine the current situation in a later section.

Room-scale tests

The first attempt to develop some technique for measuring rate of heat release in full scale was in 1978, by Warren Fitzgerald, at Monsanto Chemical.[41] The Monsanto Calorimeter involved measurements of temperatures at numerous thermocouple locations, from which a heat release rate was computed. This method, because of its uncertain computational premises and its limited measurement capacity, did not obtain acceptance.

The first room-scale test for heat release rate to win widespread acceptance was the 1982 draft ASTM room fire test.[42] This method forms the basis of all current-day room fire tests, which are only different in minor details from the 1982 draft method. Peacock & Babrauskas have reviewed the history of room fire tests in greater detail;[49] again, we will return to the current situation later in this paper.

EXAMPLES OF THE IMPORTANCE OF HEAT RELEASE RATE

To determine what is most important to consider in building fires, we first restrict ourselves to 'typical' building fires. This means we exclude as special those fires which are associated with gas or dust explosions, or where the victims are injured by direct burns from flammable clothing or faulty appliances. Instead, we consider the typical fire where occupant death or injury occurs from an ignition source not in immediate contact with this person, the fire spreads, grows, and then does or does not result in death or injury. Such fires can be broken down into their constituent phenomena:[40,44]

ignition;
flame spread;
heat release rate and, closely related, the mass loss rate;
release rates for smoke, toxic gases, and corrosive products.

The real-scale fire hazard can be assessed by tracking incapacitation or mortality of building occupants during the course of the fire. Increased hazard is identified with earlier incapacitation/mortality or with greater total numbers of victims. We now wish to determine which of the above fire phenomena, and, specifically, which variables, are most strongly associated with increased fire hazard. To examine the relative importance of these phenomena, we will consider two examples.

Example I—A single upholstered chair burning in a room

The first example will be a simple case where we consider variations on a scenario of a single upholstered chair burning in a room with a single doorway opening. The procedures detailed for HAZARD I by Bukowski *et al.*[45] and Peacock & Bukowski[46] were used to calculate the hazard for the scenarios. Fire performance data for the burning chair in the base case were taken directly from the fire properties data base included with HAZARD I. To assess the relative importance of several factors, the following variations were studied:

base case, single burning chair in room;
double heat release rate of chair;
double toxicity of materials;
halve ignition delay of burning chair from 70 to 35 s.

The general development of these fires is shown in Fig. 2, where the predicted temperatures and CO_2 levels in the upper layer of the room are given. Although other gas species could be chosen as indicators of toxicity, the CO_2 concentration is representative of the type (and shape) of curves for other gases. As expected, changing the heat release rate has a much greater effect than the change in ignition time. (Although we note that improved ignition performance can also, in some cases, *prevent* a fire from occurring. The analysis of product performance which includes both fires that occur and fires that are prevented falls into the category of risk analysis, and is outside the scope of the present paper.) The relative effect of changes in the toxicity can be seen in Table 1, as calculated from the simulations illustrated in Fig. 2.

Comparing the results for the four scenarios, it is apparent from the predicted time to death that changing the heat release rate has by far the greatest effect on the tenability of the space, reducing the time to death from greater than 600 s (the total simulation time) to about the same time as the time to incapacitation for all other scenarios.

In this simple example we have treated the burning product as if its characteristics were completely uncorrelated, that is, that we could, for example, change the ignition delay time without altering at all the heat release rate characteristics. In practice, there is very likely to be some

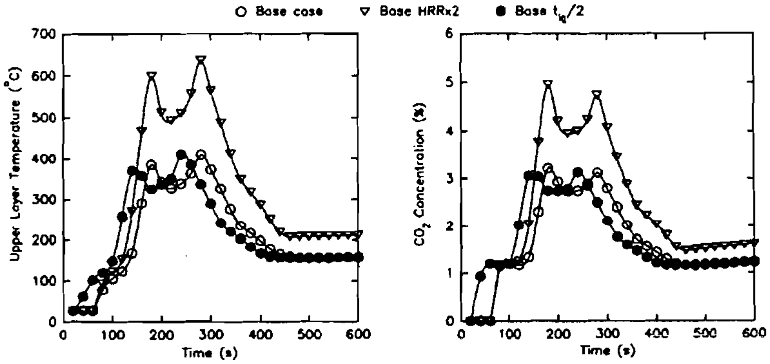

Fig. 2. Results of simulations with HAZARD I: Example I.

TABLE 1
Results for Example 1.

Scenario	*Time to incapacitation (s)*	*Time to death (s)*
Base case	180	>600
Double heat release rate	160	180
Double material toxicity	180	>600
Halve ignition delay	140	>600

degree of correlation amongst various of the reaction-to-fire properties of a product. Thus, it is also of interest, next, to look at the behavior of some actual tested products.

Example II—Multiply furnished rooms

In the previous example, only the burning in a room of a single item is considered. For a more realistic, albeit more complex example, we can turn to the study done by NIST for the Fire Retardant Chemicals Association (FRCA).[47] In the FRCA study, five different categories of products were assembled and tested in full-scale room fires. In one series, all five products were fire retardant, whereas in the other series the same base polymers were used, but without fire retardant agents. The products included upholstered chairs, business machine housings, television housings, electric cable, and electronic circuit board laminates. These products were studied thoroughly in full-scale fires, in bench-scale tests, and by computer modeling. For present purposes, however, we wish to concentrate on one aspect, the identification of the most important physical variable in these tests which is a predictor of the fire hazard.

To do this, we can consider the results in Table 2.

In this test series, the two most important measures of fire hazard were the time to reach untenable conditions (reflecting hazard to nearby occupants), and the total toxicity, expressed as CO-equivalent kilograms (reflecting hazard to far-removed occupants). The differences between the performance of the FR and non-FR product series were striking. (Within each series, the different tests conducted indicate replicates or slight scenario variations.) One might conjecture that the fire hazard performance could be predicted by the yields of CO observed for these two series. Clearly, Table 2 shows that such is not the case. Other variables, such as toxic potencies (LC_{50} values), derived

TABLE 2
Results for Example 2.

Products	*Test no.*	*Fire hazard condition*		*Predictive variable*	
		Total toxicity, expressed as (CO-equiv. kg)	*Time to reach untenable conditions in burn room (s)*	*CO yield (kg/kg)*	*Peak heat release rate (kW)*
non-FR	N1	21	110	0·22	1 590
non-FR	NX0	17	112	0·18	1 540
non-FR	NX1	16	116	0·14	1 790
FR	F1	2·6	∞	0·22	220
FR	FX0	5·5	1 939	0·23	370
FR	FX1	6·1	2 288	0·23	350
FR	FX1a	5·6	1 140	0·23	450

from the individual products tested, although more difficult to evaluate, show the same non-prediction. Likewise, time-to-ignition data for the five products in the two series show ignition time differences ranging from negligible to about two-fold. Thus, ignition behavior is also clearly unable to predict the much superior fire hazard performance exhibited by the FR products. By contrast, the peak heat release rates, shown in the last column, delineate quite clearly the difference between the two series.

The two examples presented above are only several possible illustrations of an infinite number of possible scenarios; a few may exhibit different trends. Nonetheless, these above results are consistent with numerous other studies, such as Ref. 29, and with the detailed understanding of the physics of room fires.[48]

PREDICTION OF REAL-SCALE FIRE HAZARD FROM BENCH-SCALE TESTS

Basically, the same variables—ignition, flame spread, heat release rate, and release rates for other products of combustion—can be measured in real-scale fires and in bench-scale fire tests. The ability to measure these quantities in bench-scale tests has improved enormously since the first efforts of 1959. It has become accepted practice that *all* heat release rate testing—in bench scale, in room scale, and in intermediate scale

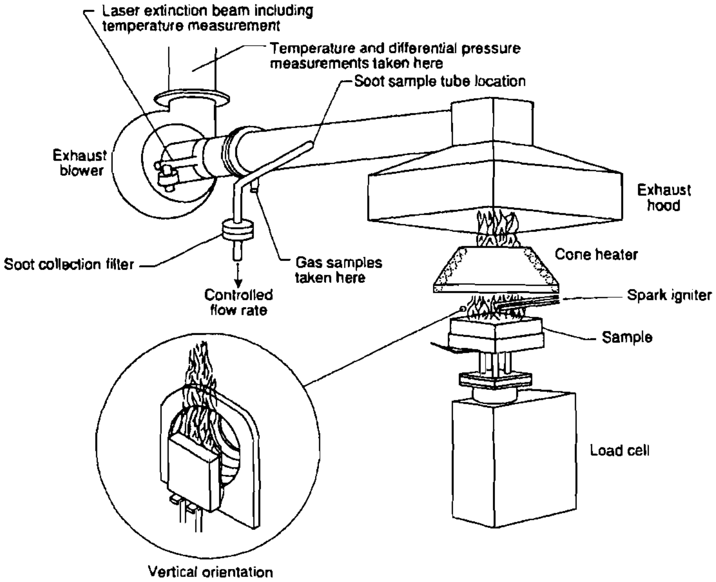

Fig. 3. A schematic view of the cone calorimeter.

(furniture calorimeters)—is done in apparatuses which are based on the oxygen consumption technique. The most widely accepted are the ones standardized by the International Organization for Standardization (ISO). ISO has adopted the Cone Calorimeter as its bench-scale method (ISO DIS 5660) for measuring HRR.[49] The same method has also been issued by ASTM as E 1354.[50] The Cone Calorimeter (Fig. 3) has been designed to measure simultaneously, not just the heat release rate, but also ignitability, smoke production, and the production of a number of toxic gas species.[51] For room-scale testing, the ISO room corner test (ISO DIS 9705) is used.[52] For testing products at an intermediate scale, open-air hood systems, again using the oxygen consumption technique, are employed. ISO has not yet worked on standardizing such 'furniture calorimeter,' but the standard most commonly specified is the one published by NORDTEST.[53] The above, then, comprise the modern toolkit for measuring HRR; while scale and appearance is different they are unified by using a common measurement technique for making the fundamental HRR measurement.

Even though the very same phenomena are measured in real-scale fires and in bench-scale tests, it does not mean that there is necessarily a simple, direct relationship between the two. In very simple cases, this can be true. For instance, if small-flame ignition is to be assessed, a bench-scale small-flame ignition test represents identically the situation occurring in the real-scale fire.

As we have seen, however, ignition variations compose but a small component of expected fire hazard. Our primary focus, instead, must be in predicting the real-scale heat release rate. Since peak hazard is associated with peak heat release rate, it is then the peak value that we wish to predict. The first successful example of such prediction has been for upholstered furniture. In an extensive NIST study on fires with residential upholstered furniture, it was found that the peak real-scale heat release rate can, indeed, be predicted from bench-scale Cone Calorimeter measurements.[59] However the relationship is not

peak real-scale HRR versus peak bench-scale HRR

but, rather,

peak real-scale HRR versus 180 s average bench-scale HRR.

An average, rather than the peak HRR is needed from the bench scale due to the physics of burning: at the time the peak HRR is being registered in the room fire, not every portion of the burning item is undergoing its peak burning—some portions are already decaying, while others are barely getting involved. Statistical considerations then lead to 180 s as a useful length of the averaging period.[54]

Another example where a more complicated relationship has to be sought is for combustible wall linings. Wickström & Göransson[55] found that, for predicting room fires caused by combustible wall linings, the heat release rate in the real-scale fires was predicted not by bench-scale heat release rate measurements alone, but by a combination of heat release rate and ignition measurements, as determined in the Cone Calorimeter. The ignition time, here, is not used to describe the ignition event. Instead, it is known that radiant ignition and flame spread are both governed by the same material properties (thermal inertia and ignition temperature) of the specimen. Thus, in the Wickström/Göransson method, use of the ignition time data allows the entire prediction to be made from the use of Cone Calorimeter data, without needing to introduce a second test for obtaining flame spread parameters. More complex models are also available[56,57] which do require input from additional tests.

SUMMARY

Reaction-to-fire tests have been in use since the early 1900s. Those most commonly used for plastics—UL 94 and the LOI test—do not predict the development of hazard in room fires. Fire deaths are most commonly the result of toxic products of combustion. The actual hazard produced depends on many factors, including the rapidity of ignition and the toxic potency of the gases. Nonetheless, it is illustrated that the *most significant predictor of fire hazard is the heat release rate.* Our ability to predict this most important aspect of fires is relatively very recent, since the first standard method for quantitatively measuring heat release rate in room fires was not available until 1982. During the 1980s, bench-scale techniques for making measurements which can predict the real-scale heat release rate were defined and put into place. Thus, all the needed tools are now at hand to enable the correct, quantitative computation of room fire hazard, based on correctly designed bench-scale tests.

REFERENCES

1. *Fire Test Standards*, 2nd edn. American Society for Testing and Materials, Philadelphia, 1988.
2. Troitzsch, J., *International Plastics Flammability Handbook. Principles–Regulations–Testing and Approval*, 2nd edn. Hanser Publishers, Munich, 1990.
3. *Tests for flammability of plastic materials for parts in devices and appliances* (*UL* 94). Underwriters Laboratories, Northbrook.
4. *Standard method of test for flammability of plastics using the oxygen index method* (*ASTM D* 2863). American Society for Testing and Materials, Philadelphia.
5. Woolson, I. H., A new method of testing fire-resisting qualities of fireproofed wood. *Engineering News*, **47**, (1902) 48–51.
6. Dunlap, M. E. & Cartwright, F. P., Standard fire tests for combustible building materials. *ASTM Proc.*, **27** (1927) 534–46.
7. Freeman, J. H., On the safeguarding of life in theaters. *Trans. ASME*, **27** (1906) 71–170.
8. British Standards Specification 476, British Standards Institution, London (1936).
9. Report of Committee on Fireproofing and Preservative Treatments, *Proc. NFPA*, **32** (1938) 93–110.
10. *Standard test method for rate of burning and/or extent and time of burning of flexible plastics in a vertical position* (*ASTM D* 568–40). American Society for Testing Materials, Philadelphia, 1940.
11. Steiner, A. J., Method of fire-hazard classification of building materials. *ASTM Bulletin* (March 1943) 19–22.
12. Standard test method for surface burning characteristics of building materials (E 84). American Society for Testing and Materials, Philadelphia.

13. Levin, B. C., Fowell, A. J., Birky, M. M., Paabo, M., Stolte, A. & Malek, D., Further development of a test method for the assessment of the acute inhalation toxicity of combustion products (NBSIR 82-2532). [US] Natl. Bur. Stand., 1982.
14. *Proceedings of NFPA Toxicity Advisory Committee Workshop on Practical Approaches for Smoke Toxicity Hazard Assessment.* NFPA, Quincy, MA, (1984).
15. Snell, J. E., (chairman) (presented by A. E. Cote). Summary Preliminary Report of the Advisory Committee on the Toxicity of the Products of Combustion. NFPA, Quincy, MA, 1984.
16. Bukowski, R. W. & Jones, W. W., The development of a method for assessing toxic hazard. *Fire J.*, **79**, 24–26, 28–29, 82.
17. Bukowski, R. W., Quantitative determination of smoke toxicity hazard—a practical approach for current use. In *Fire Safety Science—Proceedings of the First International Symposium.* Hemisphere Publishing Corp., New York, 1986, pp. 1089–100.
18. Bukowski, R. W., Strawman procedure for assessing toxic hazard. In Summary Preliminary Report of the Advisory Committee on the Toxicity of the Products of Combustion. NFPA, Quincy, MA, 1984.
19. Lawson, J. R. & Quintiere, J. G., Slide-rule estimates of fire growth (NBSIR 85-3196), [US] Natl. Bur. Stand., 1985.
20. Bukowski, R. W., Toxic hazard evaluation of plenum cables. *Fire Technology*, **21** (1985) 252–66.
21. Nelson, H. E., 'Fireform'—a computerized collection of convenient fire safety computations (NBSIR 86-3308). [US] Natl. Bur. Stand., 1986.
22. Chitty, R. & Cox, G., AKSFRS. BRE Microcomputer Package. Building Research Establishment, n.p., 1988.
23. Cooper, L. Y., A mathematical model for estimating safe egress time in fires. *Fire and Materials,* **6** (1982) 135–44.
24. Babrauskas, V., COMPF2—a program for calculating post-flashover fire temperatures (Tech Note 991). [US] Natl. Bur. Stand, 1979.
25. Mitler, H. E. & Emmons, H. W., Documentation for CFC V, the Fifth Harvard Computer Fire Code (NBS GCR 81-344). [US] Natl. Bur. Stand., 1981.
26. Tanaka, T., A model of multiroom fire spread (NBSIR 83-2718). [US] Natl. Bur. Stand., 1983.
27. Gahm, J. B., Computer Fire Code VI, Vol. I (NBS GCR 83-451). [US] Natl. Bur. Stand., 1983.
28. Nelson, H. E., Jefferson National Memorial historical site analysis of impact of fire safety features (NBSIR 84-2897). [US] Natl. Bur. Stand., 1985.
29. Bukowski, R. W., Evaluation of furniture fire hazard using a hazard-assessment computer model. *Fire and Materials,* **9** (1985) 159–166.
30. Emmons, H. W., Why fire model? The MGM Fire and Toxicity Testing. The 1985 SFPE Guise Award Lecture, Harvard/FMRC Home Fire Project Technical Report No. 73, 1985.
31. Committee on Fire Toxicology, National Research Council, *FIRE & SMOKE: Understanding the Hazards.* National Academy of Sciences. National Academy Press, Washington, 1986, pp. 105–30.
32. Thompson, N. J. & Cousins, E. W., The FM construction materials calorimeter. *NFPA Q.*, **52** (1959) 186–92.

33. Approval Standard for Class I Insulated Steel Deck Roofs (4450). Factory Mutual Research, Norwood, 1989.
34. Standard test method for heat and visible smoke release rates for materials and products (ASTM E 906). American Society for Testing and Materials, Philadelphia.
35. Sauer, J. M. & Smith, E. E., Mathematical model of a ventilation controlled compartment fire. *J. Fire Sci.*, **1** (1985) 235–84.
36. Parker, W. J., An investigation of the fire environment in the ASTM E-84 tunnel test. NBS Technical Note 945. [US] Natl. Bur. Stand., 1977.
37. Sensenig, D. L., An oxygen consumption technique for determining the contribution of interior wall finishes to room fires (NBS Technical Note 1128). [US] Natl. Bur. Stand., 1980.
38. Parker, W. J., Calculations of the heat release rate by oxygen consumption for various applications (NBSIR 81-2427). [US] Natl. Bur. Stand., 1982.
39. Tewarson, A., Flammability of polymers and organic liquids, Part I, Burning intensity (FMRC Serial 22429). Factory Mutual Research Corp., Norwood 1975.
40. Babrauskas, V. & Wickström, U. G., The rational development of bench-scale fire tests for full-scale fire prediction. In *Fire Safety Science—Proc. of the Second International Symposium,* 1988. Hemisphere Publishing, New York, 1989, pp. 813–22.
41. Fitzgerald, W. E., Quantification of fires: 1. Energy kinetics of burning in a dynamic room size calorimeter. *J. Fire and Flammability,* **9** (1978) 510–25.
42. Proposed standard method for room fire test of wall and ceiling materials and assemblies. In *1982 Annual Book of ASTM Standards,* Part 18. American Society for Testing and Materials, Philadelphia, 1982.
43. Peacock, R. D. & Babrauskas, V., Analysis of large-scale fire test data. *Fire Safety J.*, **17** (1991) 387–414.
44. Babrauskas, V., Effective measurement techniques for heat, smoke, and toxic fire gases. In *Fire: Control the Heat. . Reduce the Hazard.* QMC Fire & Materials Centre, London, 1988, pp. 4.1–4.10.
45. Bukowski, R. W., Peacock, R. D., Jones, W. W. & Forney, C. L., *HAZARD I Fire Hazard Assessment Method* (NIST Handbook 146). Natl. Inst. Stand. Tech., Gaithersburg, MD, (1989).
46. Peacock, R. D. & Bukowski, R. W., A prototype methodology for fire hazard analysis. *Fire Technology,* **26** (1990) 15–40.
47. Babrauskas, V., Harris, R. H., Jr, Gann, R. G., Levin, B. C., Lee, B. T., Peacock, R. D., Paabo, M., Twilley, W., Yoklavich, M. F. & Clark, H. M., *Fire Hazard Comparison of Fire-Retarded and Non-Fire-Retarded Products* (NBS Special Publication SP 749). [US] Natl. Bur. Stand., 1988.
48. Drysdale, D., *An Introduction to Fire Dynamics.* Wiley, Chichester, UK, 1985.
49. Draft International Standard—Fire Tests—Reaction to Fire—Rate of Heat Release from Building Products (ISO DIS 5660). International Organization for Standardization, Geneva.
50. Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter (ASTM E 1354). American Society for Testing and Materials, Philadelphia, 1990.

51. Babrauskas, V., New test methods for assessing smoke, toxic products, corrosive products, and heat release in fires. In *Flame Retardants '90.* Elsevier Applied Science, London, 1990, pp. 20–33.
52. Room Fire Test in Full Scale for Surface Products, ISO DIS 9705, International Organization for Standardization, 1989.
53. Upholstered Furniture; Burning Behaviour—Full Scale Test (NT FIRE 032). NORDTEST, Helsinki, Finland, 1987.
54. Babrauskas, V. & Krasny, J. F., *Fire Behavior of Upholstered Furniture* (NBS Monograph 173). Natl. Bur. Stand., 1985.
55. Wickström, U. & Göransson, U., Prediction of heat release rates of large scale room fire tests based on cone calorimeter results. *J. Testing and Evaluation.* **15** (1987) 364–70.
56. Mitler, H., Algorithm for the mass-loss rate of a burning wall. In *Fire Safety Science—Proc. of the Second Intl. Symp.* Hemisphere, New York, 1989, pp. 179–88.
57. Cleary, T. G. & Quintiere, J. G., A framework for utilizing fire property tests. Proceedings of the *Fire Safety Science* (to be published). 3rd International Symposium, Edinburgh, July '99.

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Sent:	Tuesday, May 06, 2008 2:22 PM
To:	CPSC-OS
Cc:	Ray, Dale
Subject:	Upholstered Furniture NPR
Attachments:	GBH Attachments 8 to 11.pdf

To: Office of the Secretary, Consumer Product Safety Commission

Please find attached the second part of the attachments to the comments by GBH International on the Upholstered Furniture NPR. A previous e-mail contained the comments.

Yours sincerely

Marcelo M. Hirschler
GBH International
2 Friars Lane - Mill Valley - CA - 94941 - USA
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UPHOLSTERED FURNITURE HEAT RELEASE RATES: MEASUREMENTS AND ESTIMATION

Vytenis Babrauskas
Materials Fire Properties
Center for Fire Research
U.S. Dept. of Commerce
National Bureau of Standards
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ABSTRACT

A new instrument, termed a furniture calorimeter, has been constructed and placed into operation for measuring furniture heat release rates based on oxygen consumption. Using the furniture calorimeter, burning rate information has been obtained on a series of 13 chairs, loveseats, and sofas, most of them specially built to permit direct comparisons of construction features. A quantitative assessment is made of the effect of fabric types, padding types (cotton batting, ordinary polyurethane foam, and California-requirements foam), and frame types. The advantages of furniture calorimeter testing over normal room fire testing are discussed. Based on these measurements, a rule is presented for estimating the heat release rate based on design factors. Finally, implications for achieving both good flame resistance and good cigarette ignition resistance are discussed.

Key words: burning rate; chairs; flammability tests; furniture; heat release rate; plastics flammability; textile flammability; upholstered furniture.

INTRODUCTION

FURNITURE FIRES ACCOUNT FOR ROUGHLY HALF OF ALL THE FIRE deaths in the United States. These are primarily divided into upholstered furniture fires and bed fires, with about half the losses in each category. Thus, efforts in reducing upholstered furniture fire losses can have a significant effect on the over-all fire problem.

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Because of many unifying characteristics, it is convenient to divide furniture fires according to the ignition mode. Smoldering fires are those started typically by a discarded cigarette, but occasionally by electric cords, fireplace embers, etc. Flaming fires are those started by matches, cooking flames, or other flaming objects. Statistical analyses indicate that for all type of residential occupancies smoldering ignitions predominate; however, analysis of individual large fires and catastrophes more often points to flaming ignitions. It is commonly considered that there is no connection between good flaming ignition performance of upholstered furniture and good cigarette ignition resistance qualities; we shall, however, re-examine this point.

A test was developed at the National Bureau of Standards nearly a decade ago for quantifying furniture resistance to cigarette ignition. This has been documented [1] and presented to the U.S. Consumer Product Safety Commission (CPSC), which has the relevant regulatory authority.

In the present work we address the initial issues associated with developing appropriate test procedures for determining the behavior of upholstered furniture specimens under flaming ignition conditions. The long-range goal of this effort is the development of bench-scale test procedures which can be used to predict, to an adequate degree, the performance of interior furnishings in full-scale in a room. Here we report the first set of findings: heat release rates for a variety of upholstered furniture, along with an initial release rate estimating rule.

SOURCES OF FLAMING IGNITION

There is a considerable amount of confusion concerning the definition of "the first item to ignite." This first item in the great majority of flaming fires is a match. This definition is not sufficiently informative. We can envision a sequence where the match ignites the match book, which is dropped into a pile of newspapers, which ignites a sofa. This suggests that for "first item to ignite" we should infer "first large item to ignite," and define its "ignition source" as the one previous step in this chain. Thus, in this study we will assume that an upholstered chair is a typical first (large) item to ignite under study.

It is possible to ignite many, but not all typical upholstered chairs with a single match. It is possible to ignite all, except the especially fire-hardened, with a small plastic wastebasket aflame with some refuse [2]. In some places, e.g., England [3], this type of observation prompted the development of a graded ignition series, where a specimen is subjected to an ignition source of increasing size. This appears to protect against children playing with matches (and bunsen burners) but not against those who drop their matches on a newspaper pile, into a wastebasket, or who try to hide their fire under a pillow. While the best-performing specimens may, in fact, fail to ignite at all when subjected to a moderate source, the more common situation is where a well-performing specimen may ignite, burn briefly, and die out, releasing negligible heat [2]. Further, data are available [2] showing that furniture items of very similar ignition potential can have widely varying burning rates. These observations suggest that of primary importance is the rate of heat release of a fire once ignited, and that a realistically large but not excessive ignition source should be chosen. A small plastic wastebasket, filled with trash can be such a source. In the present study, a gas burner simulating the performance of a wastebasket was adopted. Its characteristics are described in a later section.

In the U.S. a test for behavior of upholstered furniture subjected to flaming ignition has been promulgated by the state of California [4]. This comprises separate, bunsen-burner type tests for upholstery fabrics and for padding materials. The padding materials are not covered by fabric in the tests. One objective of this study has been to assess the useability of results from this test as a measure for describing the burning rate of full-sized upholstered furniture pieces.

RATIONALE FOR MEASUREMENTS

Full-scale evaluations of furniture burning characteristics have generally been done by conducting room fire tests (e.g., [5,6]). Room fire tests are difficult to conduct due to cost and complexity and also due to problems of reproducibility. More important, in recent years it has become possible to calculate and predict [7,8] room fires behavior *if* the heat release rate(s) of the burning object(s) and other parameters are known. Thus, it becomes feasible to separate the problem: heat release data can be obtained on test objects burning under approximate free-ambient conditions, while the effects of the enclosing room can be computed numerically. With the room fire approach, a new test may be required if a different condition, such as a change in window opening size, is prescribed. With the open testing/mathematical calculation approach, only a new computer run is required. This type of separation, it should be added, does not hold after flashover (gas temperatures > 600 °C near the ceiling, floor level radiant fluxes > 20 kW/m^2) is reached in the room. The burning rates after flashover is reached are, in fact, not simply related to the free-burn rate.

In the crudest sense, the burning rates of furniture items could be determined by burning them in the open on a weighing platform, calculating mass loss rates, and multiplying by an average heat of combustion. This is not ideal, both because numeric differentiation is required and because the effective heats of combustion may be difficult to determine and may vary during the course of the fire.

A test could be made where it is attempted to capture and measure all the heat released, both convective and radiative. This is difficult to do on any scale and would be especially difficult for full-size furniture.

Instead, the attractive features of the oxygen-consumption principle were used to design a simple test apparatus.

THE OXYGEN-CONSUMPTION BASED FURNITURE CALORIMETER

It has been known for some decades that most organic combustibles, when burned, release a nearly fixed quantity of heat *per unit oxygen consumed*. Heats of combustion per unit fuel mass vary by more than a factor of 2 for common combustibles [9]. However, the heat released per kg oxygen consumed is, to within about ± 5 percent, equal to 13.1×10^3 kJ/kg for all common combustibles. Huggett [10] has tabulated and discussed this constancy in detail.

It now becomes possible to consider a simple instrument for determining the heat release rates: all that is required is to measure oxygen concentration changes, which is easy, rather than trying to capture all the sensible heat, which is difficult. Figure 1 shows the instrument developed to take advantage of this measurement principle for upholstered furniture items. A weighing platform is included in order to document approximate heats of combustion. Heat release rates in the calorimeter are determined according to the equations developed by Parker [11]. The basic equation is

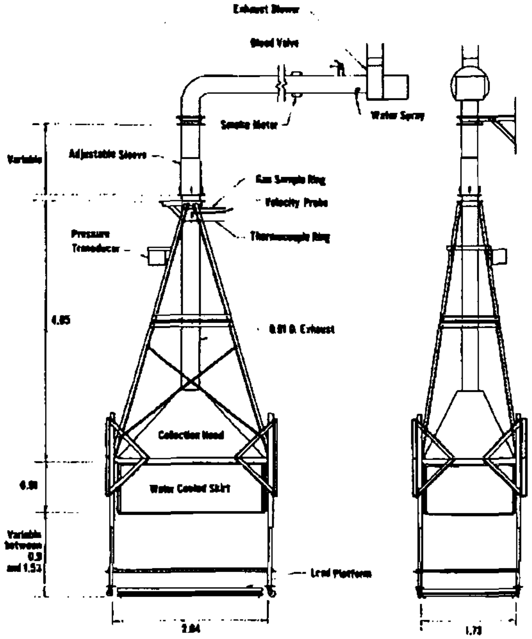
$$\dot{Q} = \frac{\Delta h_c}{r_0}\left(\dot{m}_{O_2,\infty} - \dot{m}_{O_2}\right)$$

where $\dot{Q}$ is the heat release rate (kW), $\Delta h_c/r_0$ is the constant 13.1×10^3 kJ/kg, $\dot{m}_{O_2}$ is the oxygen flow in the exhaust system during combustion (kg/s), and $\dot{m}_{O_2,\infty}$ is the oxygen flow without combustion. Additional theoretical considerations and operational details are reported in [12].

Specimens releasing more than ~2000 kW were tested under similar conditions in a large rig with a capacity of over 6000 kW, with lower resolution but similar in principle to the one depicted in Figure 1.

Ignition of test specimens was accomplished with a gas burner simulating a wastebasket fire placed adjacent to the left chair arm (Fig. 2). Earlier testing [2] had determined the wastebasket burning rate. For the present tests this was approximated as 50 kW for 200s (Fig. 3). A flux map of this burner is shown in Figure 4.

For characterizing the ignition potential for other fuel items, a single point target irradiance measurement was provided. This was made with a Gardon gage facing the fire 0.5 m in front of the specimen and at a height of 0.5 m.



All dimensions in meters

Figure 1. View of calorimeter

TEST SPECIMENS

One objective of the present tests was to be able to isolate the influence of different furniture materials. For this reason, the majority of the specimens were custom-made. These specimens (F21 through F26 and F29 through F32) were made by a furniture maker using normal construction practices, but varying one feature at a time: padding, fabric, frame, or total size. Table 1 gives details of the test pieces. Both ordinary and "California" (sold as meeting California state requirements—this was checked using the specified test method [4]) foams were procured from normal commercial wholesale channels. Figures 5 through 8 show some of the test specimens, along with views during peak burning.

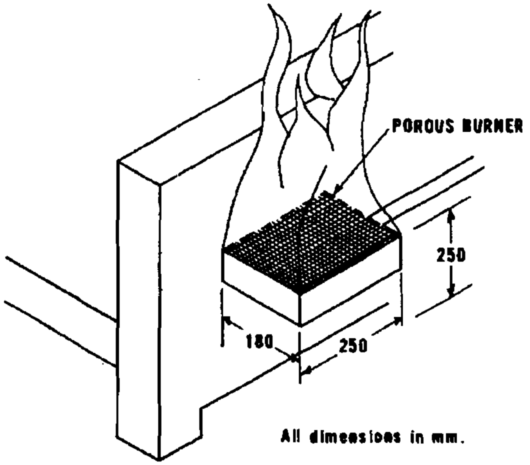


Figure 2. Wastebasket simulation burner used as the ignition source

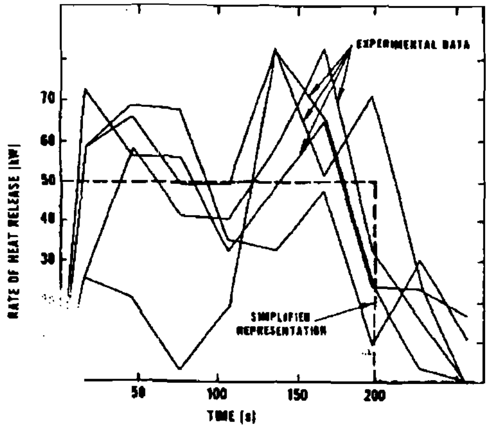


Figure 3. Measured wastebasket heat release rates, along with adopted simplified representation

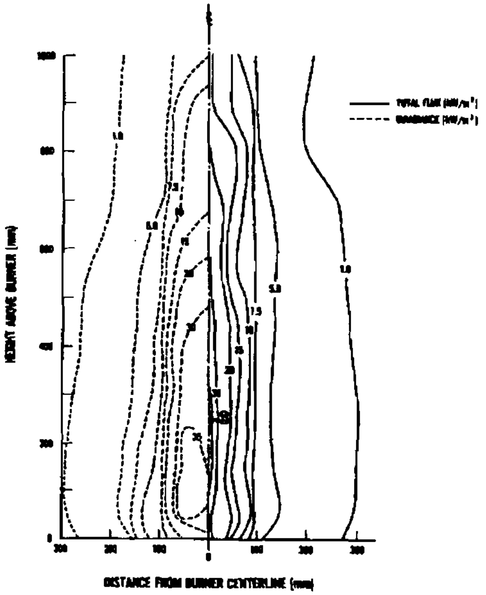
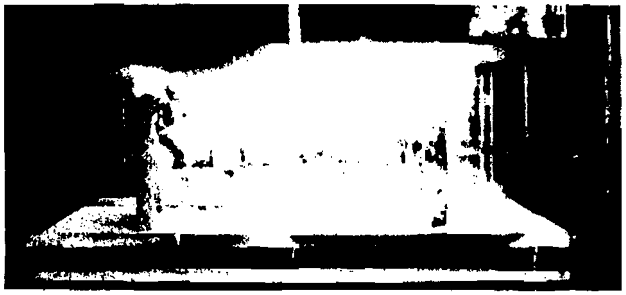


Figure 4. Fluxes measured at the wastebasket simulation burner (in a vertical plane adjacent to the 250 mm burner edge, which is against a non-combustible wall)

(a) Before test *(b) near peak burning time*

Figure 5. Chair F21

(a) Before test



(b) Near peak burning time

Figure 6. Chair F31

None of the test specimens included fire hardened constructions since such are not readily available on the commercial market.

TEST OBSERVATIONS

The ignition source burner successfully ignited all test specimens. Ignition times were short—on the order of 15 s for thermoplastic fab-

(a) Before test

(b) Near peak burning time

Figure 7. Chair F32

(a) Before test *(b) Near peak burning time*

Figure 8. Chair F28

Table 1. Test specimens

Chair	Tests	Mass (kg)	Padding Material	Fabric	Frame
F21	T19,T46	28.3	Calif. Foam	Polyolefin	Wood
F22	T24	31.9	FR Cotton Batting	Cotton	Wood
F23	T23	31.2	FR Cotton Batting	Polyolefin	Wood
F24	T22	28.3	Calif. Foam	Cotton	Wood
F25	T29	27.8	Non-Calif. Foam	Polyolefin	Wood
F26	T25	19.2	Calif. Foam	Polyolefin	Wood (Min. Weight)
F27	T26	29.0	Foam, Cotton, Polyester	Cotton	Wood
F28	T28	29.2	Foam, Cotton, Polyester	Cotton	Wood
F29	T27	14.0	Non-Calif. Foam	Polyolefin	Polypropylene
F30	T30	25.2	Non-Calif. Foam	Polyolefin	Polyurethane
F31	T31,T37	40.0	Calif. Foam	Polyolefin	Wood (Loveseat)
F32	T38	51.5	Calif. Foam	Polyolefin	Wood (Sofa)
F33	T18	39.2	Foam, Cotton	Cotton	Wood (Loveseat)

rics—and somewhat longer for cellulosic ones. Exact times were not recorded because of the difficulty of observing ignition obscured by the burner flame. As a measure of the time scale, the time to peak rate of heat release is considered much more important, as discussed below. The left (occupant's view) side arm, being adjacent to the burner, was the first to burn. From there flaming usually progressed to the outside back of the chair. A little later flames would start across the seat cushion and the inside back. The upholstery, on the right side arm melted in about 80-120 s for the case of thermoplastic fabrics. This allowed rapid fire involvement of the foam underneath. In the case of cellulosic fabrics, the spread was much slower; the right side arm typically ignited not from radiation at a distance, but at the time when continuous flame spread reached it, at about 250 s. The front of the chair was the last to get involved in all cases.

Most specimens showed some pool burning underneath the chair since even the cotton batting units had a polyolefin dust cover underneath the seat deck which melted in the fire. Some California foam specimens showed spurting of burning liquified polyurethane foam in small streams at the side. Neither this phenomenon nor the pool burning was judged to provide any significant increase in other item ignition potential, beyond that due to high radiant heat fluxes. The active burning period normally did not last beyond about 1800 s, since in that time the majority of foam and fabric would be consumed. The total burning time is very difficult to define since the last bit of smoldering may not be extinguished for several hours. Generally by about 1800 s the heat release rate was very small, about 50 to 100 kW; at 3600 s it was around 25 kW. For wood frames, total collapse had occurred by about 1500 s. For the polyurethane frame specimen, F30, collapse had occurred by 1200 s, while for the polypropylene frame specimen, F29, collapse was at around 900 s. This difference could be anticipated since the F29 frame melted during the burning and, in fact, contributed to the fire at the peak burning time, while the F30 frame was not thermoplastic and tended instead to char.

Tests were stopped and data gathering discontinued when all flaming had ceased. Most items slowly smoldered for several more hours, producing little heat.

RESULTS OF MEASUREMENTS

A summary of the data is presented in Table 2. Included are two repeat tests, which show agreement to better than 10%. Detailed performance is illustrated for specimen F21 in Figures 9 and 10. For purposes of this preliminary analysis, it was considered that there are two primary variables of interest—the peak rate of heat release and the time to reach the peak. The peak intensity values are needed to determine the worst room fire behavior. The time to reach the peak is also considered important because in many fires detection may be feasible at or very shortly after ignition. Thus, time for occupant escape can be partly controlled by the fire growth rate.

Table 2. Summary of test data

Chair	Test	Mass (kg)	Time to Peak (s)	Maximum $\dot{m}$ (g/s)	Maximum $\dot{Q}$ (kW)	Total Q (MJ)	Δh_c Near Peak (MJ/kg)	Δh_c Average (MJ/kg)	Peak Target Irradiance (kW/m^2)
F21	T19	28.2	280	N.A.	1970	440	N.A.	18.1	49.
	T45*	28.3	260	83	2130	443	26.4	18.4	42.
F22	T24	31.9	910	25	370	425	14.8	14.9	3.7
F23	T23	31.2	450	42	700	461	16.8	16.1	14.
F24	T22	28.3	650	46	700	369	15.1	14.6	19.
F25	T29	27.8	260	80	1990	419	24.8	17.0	46.
F26	T25	19.2	240	61	810	300	13.2	18.0	32.
F27	T26	29.0	570	58	920	519	15.7	20.3	24.
F28	T28	29.2	420	42	730	369	17.2	14.9	12.
F29	T27	14.0	220	72	1950	446	27.1	35.1	39.
F30	T30	25.2	235	41	1060	363	26.0	20.9	17.
F31	T31	39.6	N.A.	N.A.	>2500	N.A.	N.A.	N.A.	>35.
	T37*	40.4	230	130	2890	614	22.2	17.5	99.
F32	T38*	51.5	250	145	3120	714	21.5	18.9	N.A.
F33	T18	39.2	560	75	940	453	11.9	13.9	N.A.

N.A. – Not Available

* – Test conducted in large test rig

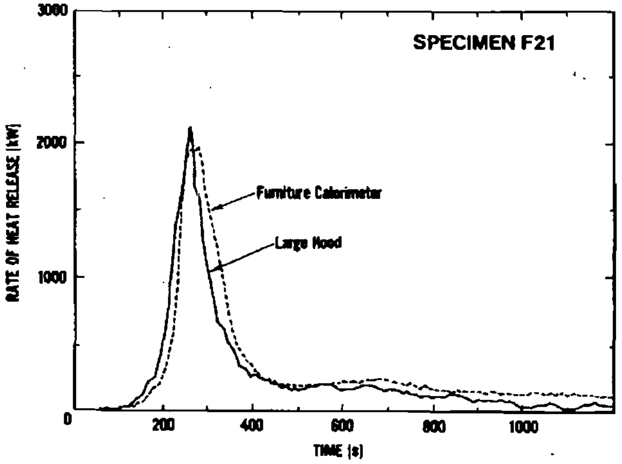


Figure 9. Rate of heat release for specimen F21

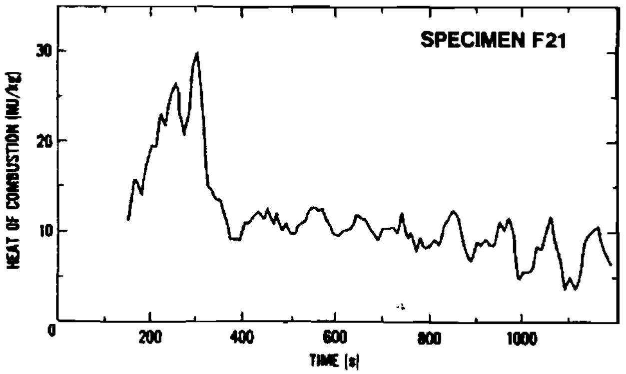


Figure 10. Effective heat of combustion for specimen F21

Table 3 shows the ranked peak times. Three distinct groups of results appear. Specimen F22, while showing flaming combustion from about 100 s to 1200 s, did not show a substantial rate of heat release peak (Fig. 11). The highest numerical value was registered at 910 s. Specimens F24, F27, F33, F33, F23, and F28 showed peak times in the range of 420-650 s. Finally, specimens F21, F25, F32, F30, F31, and F29 burned rapidly and showed peaks in the range of 220-280 s. The relative ranking within each of these groups is not considered significant. The constitution of each of these groups is striking, however. Clearly the slowest fire development occurred with an all-cellulosic construction. The fastest fire buildup happened with polyurethane foam padding combined with thermoplastic fabric upholstery. Constructions using cellulosic fabrics with polyurethane foam padding or, conversely thermoplastic fabrics with cotton batting showed a similar, intermediate buildup time. Mixed type fillings (e.g., both foam and batting in one chair) also fall into this category. It can be noted that foam type, i.e., whether ordinary or "California" type, had no effect on time to peak.

Peak rates of heat release are ranked in Table 4. Again, three distinct levels of performance can be seen. The all-cellulosic specimen, F22, performed the best, releasing only 370 kW at peak. Next came a large number of specimens clustered in an intermediate heat release range, 700 to 1060 kW. Finally came a group showing rates 2 to 4 times again as large as the previous, with the values ranging from 1950 kW to 3120 kW. With two exceptions, the members of the best, intermediate, and

Table 3. Ranked Peak Times

Specimen	Time to Peak (s)	Padding	Fabric
F22	910	Cotton	Cotton
F24	650	PU Foam, C*	Cotton
F27	570	Mixed	Cotton
F33	560	Mixed	Cotton
F23	450	Cotton	Polyolefin
F28	420	Mixed	Cotton
F21	280	PU Foam, C	Polyolefin
F25	260	PU Foam, NC	Polyolefin
F32	250	PU Foam, C	Polyolefin
F26	240	PU Foam, C	Polyolefin
F30	235	PU Foam, NC	Polyolefin
F31	230	PU Foam, C	Polyolefin
F29	220	PU Foam, NC	Polyolefin

*PU = Polyurethane; C = California Foam;
NC = Not California Foam

Table 4. Ranked peak heat release values

Specimen	Peak $\dot{Q}$ (kW)	Padding	Fabric
F22	370	Cotton	Cotton
F24	700	PU Foam, C*	Cotton
F23	700	Cotton	Polyolefin
F28	730	Mixed	Cotton
F26	810	PU Foam, C	Polyolefin
F27	920	Mixed	Cotton
F33	940	Mixed	Cotton
F30	1060	PU Foam, NC	Polyolefin
F29	1950	PU Foam, NC	Polyolefin
F21	1970	PU Foam, C	Polyolefin
F25	1990	PU Foam, NC	Polyolefin
F31	2890	PU Foam, C	Polyolefin
F32	3120	PU Foam, C	Polyolefin

*PU = Polyurethane; C = California Foam;
NC = Not California Foam

lowest groups were the same for both the time to reach the peak and for the peak burning rate itself. The differing ones were F26 and F30. Both of these have thermoplastic upholstery and polyurethane foam padding. Chair F26 was a "minimum weight" specimen, so while it reached its peak burning rate quickly it did not have as much fuel to burn as other specimens. Chair F30 had the rigid polyurethane foam frame. The results indicate that while replacing cotton batting padding with flexible polyurethane foam normally acts to increase the burning rate significantly, replacing the wood frame with a comparable polyurethane one not only did not increase the heat release rate but in this case actually decreased it. This is striking but perhaps not unexpected since the rigid polyurethane frame predominantly charred rather than melted.

A detailed comparison of the effects of construction features is presented in Figures 11 and 12 and in Tables 5 through 8. Table 5 shows the effect of different padding types, for a given fabric. Type of foam ("California", or ordinary) is seen to have no effect. For a given fabric type, however, cotton batting construction produces less than half the rate of heat release as polyurethane foam or mixed types. Mixed type constructions can be of various sorts but—within a fairly wide amount of scatter—show heat release similar to the all-foam and not to the all-cotton batting types.

The effect of fabric types is explored in Table 6. For a given filling material type, the cellulosic (cotton) fabric specimens had a rate of heat release of less than half that of the thermoplastic (polyolefin) fabric specimens.

Within a given construction type, total specimen mass can be expected to be a major factor. The relationship is shown for polyurethane foam types in Table 7. An approximately linear dependence on specimen mass is seen on the heat release rate, with no effect on time to peak.

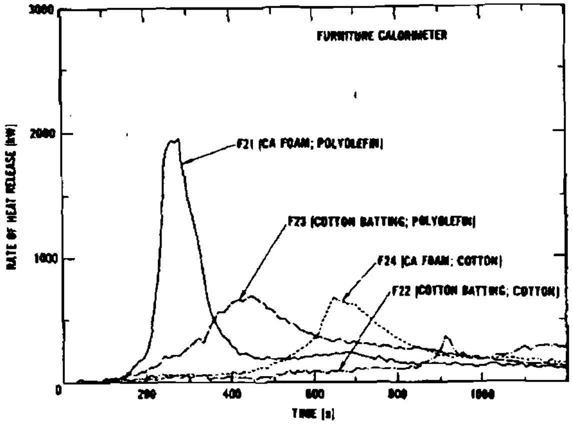


Figure 11. Effect of specimen padding and fabric on rate of heat release

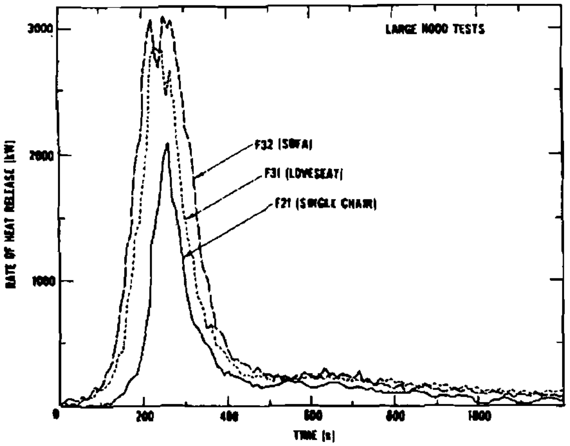


Figure 12. Effect of specimen mass on rate of heat release

Table 5. Effect of padding type for specimens with similar fabrics

Specimen	Peak $\dot{Q}$ (kW)	Time to Peak (s)	Padding	Fabric
F21	1970	280	California Foam	Polyolefin
F25	1990	260	Non-California Foam	Polyolefin
F21	1970	280	California Foam	Polyolefin
F23	700	450	Cotton	Polyolefin
F24	700	650	California Foam	Cotton
F22	370	910	Cotton	Cotton
F27	820	570	Mixed	Cotton (not identical to above)
F28	730	420	Mixed	Cotton (not identical to above)

Table 6. Effect of fabric type for specimens of similar construction and padding

Specimen	Peak $\dot{Q}$ (kW)	Time to Peak (s)	Fabric	Padding
F24	700	650	Cotton	California Foam
F21	1970	280	Polyolefin	California Foam
F22	370	910	Cotton	Cotton
F23	700	450	Polyolefin	Cotton

Table 7. Effect of specimen mass on polyurethane foam padded specimens of similar construction

Specimen	Peak $\dot{Q}$ (kW)	Time to Peak (s)	Mass (kg)	Comments
F26	810	240	19.2	Minimum Weight Chair
F21	1970	280	28.2	Standard Chair
F31	2890	230	40.0	Loveseat
F32	3120	250	51.5	Sofa

Table 8. Effect of frame type for specimens with similar padding and fabrics

Specimen	Mass (kg)	Peak $\dot{Q}$ (kW)	Peak $\dot{Q}$ ÷ Mass	Time to Peak (s)	Frame	Foam	Fabric
F26	27.8	1990	72	260	Wood	Non-Calif.	Polyolefin
F30	25.2	1060	42	235	Polyurethane	Non-Calif.	Polyolefin
F29	14.0	1960	139	220	Polypropylene	Non-Calif.	Polyolefin

Finally, frame type is seen to have a significant effect on the peak rate of heat release, though not on the time to reach the peak (Table 8). Traditional wood framing is shown to exhibit an intermediate behavior. Structural plastic foam chair frames are available in two types—thermoplastic (polypropylene and polystyrene) and thermosetting (rigid polyurethane). Polystyrene frames were not tested because they are used only in specialized applications and are not readily available. The chair with the polypropylene frame, F29, showed a rate of heat release almost identical to the comparable wood frame unit, F25. It, however, had only half the mass of F25. Thus, on a mass basis it would have to be considered twice as fast burning. (Component weight breakdowns are not available, but Table 7 suggests that for specimens using wood or plastic frames it is not unreasonable to approximate rates of heat release on the basis of total mass.) The polyurethane frame specimen, F30, showed considerably slower burning, for a roughly similar specimen mass. Apparently this frame is not only slow to contribute to the fire itself, but also by maintaining its integrity it can help reduce the role of fuel contribution from the uncovering of fresh fuel. Wood frames, by contrast, tend to fail in a fire at metal connection points.

TARGET IRRADIANCE

Peak target irradiance values are also given in Table 2. In [2] a simplification was established by dividing target fuels into three groups. The "especially easily ignitable" ones could ignite at an irradiance of 10 kW/m^2. "Normal" ignitability level was taken as 20 kW/m^2, while "difficult to ignite" objects corresponded to 40 kW/m^2. The furnishings examined in [2] were primarily slow-burning institutional and office furniture, as contrasted to the residential type items used in the present series. A comparison between the maximum radiant flux values observed during the course of the present tests and those recorded in the previous test series is shown in Figure 13. The fluxes, for a given peak mass loss rate, were substantially lower in the present series. This is partly explained by the fact that the relationship derived from the earlier tests was taken on a worst case basis. In those tests there was a substantial difference between worst case and average or typical performance. In the present case there is little deviation from a single relationship, as shown by the close fit of points in Figure 13. Additional study of the relationship between an item's mass loss rate and the target irradiance values seems warranted.

EFFECTIVE HEATS OF COMBUSTION

For modeling room fires, for estimating fuel loads and for other purposes, it is often desirable to know approximate heats of combustion for furniture. The effective heat of combustion is defined here as the heat release rate divided by the mass loss rate. A typical computed effective heat of combustion curve is shown in Figure 10 for specimen F21. Results for all the specimens are shown in Table 2, computed both for the whole period of active burning and for the time near the peak. In Table 9, a summary is given, grouped according to type of construction. Differences in padding and fabric do make some difference, but for wood-framed specimens most effective heat of combustion values are concentrated in the narrow range of 15 to 18 MJ/kg. Polypropylene framed construction, however, results in a significantly higher value, due to the high value of the net heat of combustion for polypropylene—43.2 MJ/kg [9]. The average effective value for specimen F29 was 35 MJ/kg, approximately double that for the others. Most specimens showed a behavior similar to F21—higher initial values of the heat of combustion were followed by lower values for charring frame combustion.

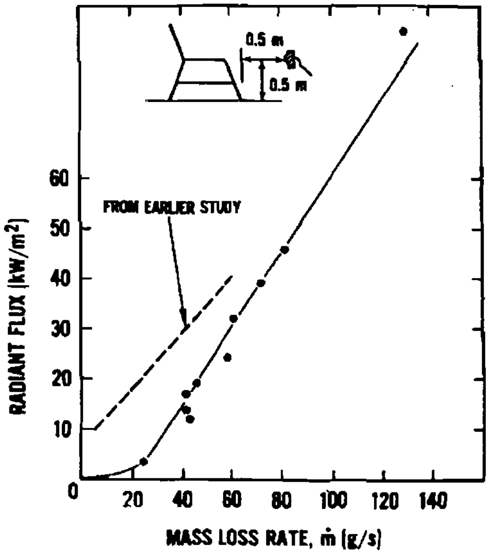


Figure 13. Relationship between mass loss rate and target irradiance

Table 9. Effect heats of combustion (averaged over entire test period)

Construction				
Padding	Fabric	Frame	Specimens	Average Effective Heat of Combustion (MJ/kg)
PU Foam	Polyolefin	Wood	F21, F25, F26, F31, F32	17.9
PU Foam	Cotton	Wood	F24	14.6
Mixed	Cotton	Wood	F27, F28, F33	13.9-20.3
Cotton	Polyolefin	Wood	F23	16.1
Cotton	Cotton	Wood	F22	14.9
PU Foam	Polyolefin	Polyurethane	F30	20.9
PU Foam	Polyolefin	Polypropylene	F29	35.1

ANALYSIS FOR ESTIMATION

The eventual goal of the present investigations is to develop a bench-scale test protocol whereby samples are cut from upholstered chairs and tested for rate of heat release and other properties. Testing full-sized specimens would then not be required. This procedure is not yet available. Furthermore, in some cases, say for fire hazards surveying of existing buildings and occupancies, this may never be appropriate. Thus, at this time, based on the existing test data, it was found that a useful rule can be constructed. The rule states that the peak heat release rate, $\dot{Q}_{peak}$, in kilowatts, can be approximated by a series of factors:

$$\dot{Q}_{peak} = (\text{mass factor}) \times (\text{frame factor}) \times (\text{style factor}) \times (\text{padding factor}) \times (\text{fabric factor})$$

The factors are computed as follows:

$$\text{Mass Factor} = 64. \times (\text{total mass, kg})$$

$$\text{Frame Factor} = \begin{cases} 1.0 \text{ for wood} \\ 0.6 \text{ for (rigid) polyurethane foam} \\ 2.0 \text{ for (thermoplastic) polypropylene foam} \end{cases}$$

$$\text{Style Factor} = \begin{cases} 1.0 \text{ for plain, primarily rectilinear construction} \\ 1.5 \text{ for ornate, convoluted shapes, with} \\ \text{intermediate values for intermediate shapes} \end{cases}$$

$$\text{Padding Factor} = \begin{cases} 1.0 \text{ for polyurethane foam, ordinary or California} \\ 0.4 \text{ for cotton batting} \\ 1.0 \text{ for mixed materials filling} \\ 0.4 \text{ for polychloroprene foam}^{*} \end{cases}$$

$$\text{Fabric Factor} = \begin{cases} \text{1.0 for thermoplastic fabrics (fabrics which melt prior to burning)} \\ \text{0.4 for cellulosic fabrics (cotton; also rayon, line, etc.)} \\ \text{0.25 for PVC/PU type coverings**} \end{cases}$$

The above rule is useful only for estimating the behavior of pieces generically similar to the ones included in the testing program. Thus single-piece molded chairs, bean bag chairs, built-in furniture and other specialty items are not included. A few of these types were included in an earlier [5] study, where some observations on details of burning are recorded.

A comparison between actual heat release values and ones estimated by the above rule is given in Figure 14. It is not appropriate to quantify the goodness-of-fit of this relationship, since predictive value is expected to vary according to how close the construction resembles these chosen as "typical." The chosen frame and style factors are very general. Additional studies of a wider range of specimens could produce more detailed factor variables and ranges.

Minimum time to peak can be estimated as

≅ 250 s for thermoplastic fabrics over polyurethane foam
≅ 900 s for cellulosic fabrics over cotton batting
≅ 550 s for all others.

based on the selected scenario of a wastebasket fire ignition. These times would be significantly greater if a smaller ignition source were used. The peak release *value*, however, can be considered independent of ignition source type, provided specimen ignition is achieved.

ON ACHIEVING BOTH CIGARETTE IGNITION RESISTANCE AND GOOD FLAMING BEHAVIOR

From furniture cigarette ignitability tests, it is seen that cellulosic fabrics perform generally less well than thermoplastic ones and that polyurethane foams might be preferred because, unlike cotton batting, they do not have to be specially treated to achieve cigarette ignition resistance [1]. Thus, while at first glance cigarette resistance and good flaming behavior might seem antagonistic goals, this need not be the case. Some readily available materials are known to perform well in both cases—wool fabric and polychloroprene foams are such examples. Both of these have the drawback of being relatively costly. Other possibilities are the PVC/PU type coverings mentioned earlier. These tend to show good behavior in both cases, but may not be acceptable from the point of view of comfort.

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*Estimate based on extrapolation from earlier work [13]. This value would also be applicable to the best available highly retardant treated polyurethane foams but in practice this distinction cannot be made without detailed testing.

**This is an extension based on recent unpublished work. Into this group of coverings are placed those which have a thick layer of polyvinylchloride (PVC) or polyurethane (PU) material supported on a fabric scrim. The construction is often found in washable waiting room chairs and in imitation leather chairs.

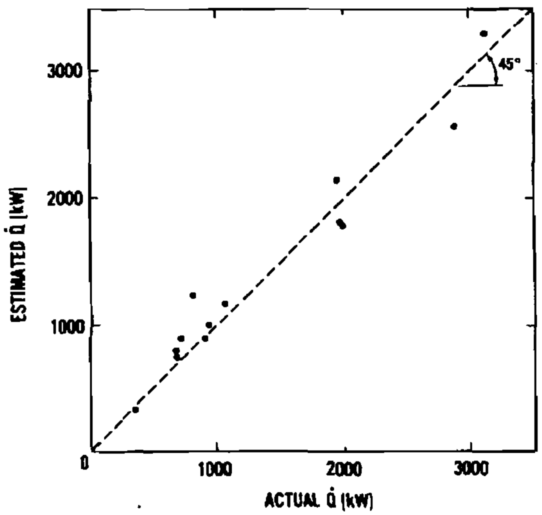

Figure 14. Relationship between actual and estimated peak values of rate of heat release

It is, however, likely that comfortable designs can be worked out which combine materials of modest cost in such a way as to achieve good overall performance for both cigarette ignition and flaming situations. Polyurethane foams are, for various manufacturing reasons, much preferred in the furniture industry. It has been seen [13] that it is possible to produce highly fire retardant polyurethane foams that have performance similar to polychloroprene. Unfortunately, costs and foam density are also comparable. A more fruitful approach may be to protect polyurethane foams with an interliner. Polychloroprene interliners intended for this use have recently come on the market. While this does not reduce the fuel load, it can delay fire development and reduce peak burning rates. When a heavy cellulosic fabric is used on polyurethane foam, it burns slowly when subjected to flames and does not expose the foam itself to flames for some time; however, it is difficult to achieve cigarette ignition resistance with a heavy cellulosic fabric. On the other hand, it was seen in the present test series that common thermoplastic fabrics tend to melt quickly when exposed to heating. Thus, they expose the foam to rapid heating from flames and from radiation early in the fire. An interliner may only provide a modest additional benefit when used under a cellulosic fabric but can be of significant benefit under a thermoplastic one. The use of some early polychloroprene-based interliners has been studied [5,13]. An extensive testing program in Great Britain resulted in recommendation for the use of cotton cambric as an interliner [14]. Additional cigarette resistance and durability can be imparted to such a cambric by bonded aluminized and thermoplastic layers, as has been done in experimental systems.

For the choice of fabrics, additional investigation is likely to show modestly priced types beyond the PVC/PU films that can have both smolder resistance and good resistance to rapid flame propagation. Since poor flaming condition behavior is largely attributed to the fabric melting away and opening up quickly, charring fiber materials, such as modacrylics and matrix fabrics, should be investigated.

SUMMARY

The advantages of open—as opposed to room—fire testing have motivated the construction of an oxygen consumption based furniture calorimeter. The primary effort described here generated comparative burning rate data on a set of upholstered furniture pieces where only one construction feature was varied at a time. The findings showed that for the range of constructions examined:

(a) Furniture using polyurethane foams with retardants added to meet California state requirements did not show any reduction in rate of heat release compared to ordinary polyurethane foams.
(b) For foam-paded chairs, the rate of heat release was proportional to specimen mass, i.e., for comparable specimens, those that weighed more showed higher rates of heat release. This indicates that any realistic testing or evaluation procedure must include both testing of bench-scale specimens and consideration of object total mass.
(c) Furniture using padding materials made of cotton batting showed lower rates of heat release and slower fire buildup than those using polyurethane foams or battings of mixed fibers.
(d) Furniture using cellulosic fabrics showed lower rates of heat release and slower fire buildup than those using thermoplastic fabrics. Cellulosic/thermoplastic blends were not investigated.
(e) Structural foam frames showed widely differing behaviors. A frame of a charring plastic was seen to give a better lower heat release rate than a wood frame, while a melting, thermoplastic frame material led to a substantially greater heat release.
(f) A very approximate set of rules was suggested for estimating the rate of heat release of upholstered furniture based only on known weights and construction. This can be useful in hazards surveying work.

Finally, it is emphasized that limited heat release behavior during flaming exposure and good cigarette ignition resistance are not necessarily mutually exclusive and that reasonable designs can enhance both. Flexibility of choice in the marketplace thereby may be traded off against enhanced fire safety performance.

REFERENCES

1. Loftus, J.J., Back-up report for the proposed standard for the flammability (cigarette ignition resistance) of upholstered furniture, PFF6-76, Nat. Bur. Std. (U.S.), NBSIR 78-1438 (1978).
2. Babrauskas, V., Will the second item ignite? Fire Safety J. *4*, 287-292 (1982).
3. Palmer, K.N., Paul, K.T. and Taylor, W., Test specifications for fire properties of bedding and upholstered furniture, Dept. of the Environment, Building Research Establishment, London (1979).
4. Requirements, test procedure and apparatus for testing the flame retardance of resilient filling materials used in upholstered furniture (Technical Information Bulletin 117), State of California Department of Consumer Affairs, Bureau of Home Furnishings, Sacramento (January 1980).
5. Babrauskas, V., Full-scale burning behavior of upholstered chairs, Nat. Bur. Std. (U.S.) Tech. Note 1103 (1979).
6. Pape, R., *et al.*, Semistochastic approach to predicting the development of a fire in a room from ignition to flashover. Program documentation and users guide, RFIRES. IIT Research Institute, Chicago (1976). NTIS No. PB-278643.
7. Pape, R. and Waterman, T.E., Understanding and modeling preflashover compartment fires, Design of Buildings for Fire Safety (ASTM STP 685), pp. 106-138, E.E. Smith and T.Z. Harmathy, eds., American Society for Testing and Materials, Philadelphia, PA (1978).
8. Mitler, H.E. and Emmons, H.W., Documentation for CFC-V, The fifth Harvard computer fire code, Nat. Bur. Stand. (U.S.), NBS-GCR-81-344 (1981).
9. Fire Protection Handbook, pp. 4-122, National Fire Protection Association, Quincy, MA (1981).
10. Huggett, C., Estimation of rate of heat release by means of oxygen consumption measurements, Fire and Materials, *4*, 61-65 (1980).
11. Parker, W.J., Calculations of the heat release rate by oxygen consumption for various applications, Nat. Bur. Std. (U.S.), NBSIR 81-2427 (1982).
12. Babrauskas, V., Lawson, J.R., Walton, W.D. and Twilley, W.H., Upholstered furniture burning rates measured with a furniture calorimeter, Nat. Bur. Std. (U.S.), NBSIR 82-2604.

13. Babrauskas, V., Combustion of mattresses exposed to flaming ignition sources, Part II. Bench-scale tests and hazard analysis. Nat. Bur. Std. (U.S.), NBSIR 80-2186 (1981).
14. Fire research on cellular plastics: The final report of the Products Research Committee, Washington, D.C. (1980).

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UPHOLSTERED FURNITURE ROOM FIRES—MEASUREMENTS, COMPARISON WITH FURNITURE CALORIMETER DATA, AND FLASHOVER PREDICTIONS

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ABSTRACT

This paper describes a series of room fire tests using upholstered furniture items for comparison with their open burning rates, previously determined in a furniture calorimeter. For the four tests conducted good agreement was seen in all periods of the room fires, including post-flashover, noting that only fuel-controlled room fires were considered. Difficulties in making accurate mass and heat flow measurements in the room's window opening were found, and it is suggested that with present day instrumentation only exhaust stack measurements are reliable. Finally, a number of simplified rules or theories for predicting room flashover based on room physical properties and open-burning heat release values were examined and compared. Broad agreement was generally found, with recommended ones selected on the basis of well-controlled asymptotic behavior.

Key words: Burning rates; flashover; furniture calorimeter; heat release rates; room fires; upholstered furniture.

INTRODUCTION

A TECHNIQUE WAS RECENTLY DEVELOPED FOR DETERMINING THE open, free burning rate of furniture items using oxygen consumption [1,2]. The apparatus, termed a "furniture calorimeter" can be used to determine the heat release rate, mass loss rate, and gas (CO, CO_2, and O_2

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depletion) and smoke production rates of any combustible solid, standing on the floor and of suitable physical size. Two apparatus versions are in use at the National Bureau of Standards (NBS), the larger having a capacity in excess of 7000 kW. These apparatuses represent an open burning condition since air entrainment is axisymmetric and essentially unrestricted, while surfaces which could act as heat radiators are either far away or are water-cooled. The capacity is governed by the maximum flow which can be collected completely by the hood without spillage. The present paper is a continuation of ongoing explorations into the uses and applications of furniture calorimeter data.

Furniture or another discrete combustible is most often a hazard, not when burned in an open field but, rather, inside a room. Traditionally this behavior was measured by building full-sized room fires. Yet simple theoretical arguments show that such room fire data lack generality and often can not be extrapolatable to rooms other than the test room [3]. It was also suggested that open burning rates have more useful generality. This was the motivating reason for the original furniture calorimeter work. The reasoning, while plausible, had to be verified. Thus, it was undertaken to construct a room of fixed size but with varying opening sizes and shapes, in which furniture specimens identical to those previously tested in the furniture calorimeter would be burned. Three basic questions were to be answered:

1. Is the heat release rate before flashover the same in the room fire as in the furniture calorimeter? A rather modest room size was picked to make for a strenuous comparison.
2. How can the flashover condition best be predicted? For this, the flashover model of [3] and more refined models would be considered.
3. Does the furniture burning rate increase appreciably after room flashover, compared to the free burn rate? This required sizing the window opening small enough to ensure flashover but not so small as to cause the post-flashover fire to become ventilation-controlled. (Furniture burning in ventilation-controlled fires deserves careful study but has yet to be undertaken, for reasons of cost).

EXPERIMENTAL ARRANGEMENTS

An experimental room was constructed inside the NBS large-scale fire test facility, as shown in Figures 1 and 2. The walls and ceiling materials were 16 mm thick, Type X gypsum wallboard, furred out on steel studs and joists. Floor construction was normal-weight concrete. In addition to the instrumentation indicated, the room was equipped with an instrumented exhaust collection system outside the window opening. The exhaust system could handle fires up to over 7000 kW size. An array of velocity probes and thermocouples, together with O_2, CO_2, and CO measurements permitted the heat release to be determined according to the principle of oxygen consumption [4]. Figure 1 also shows the location where a gas burner was used to check this calibration (this gas burner was removed prior to testing furniture specimens).

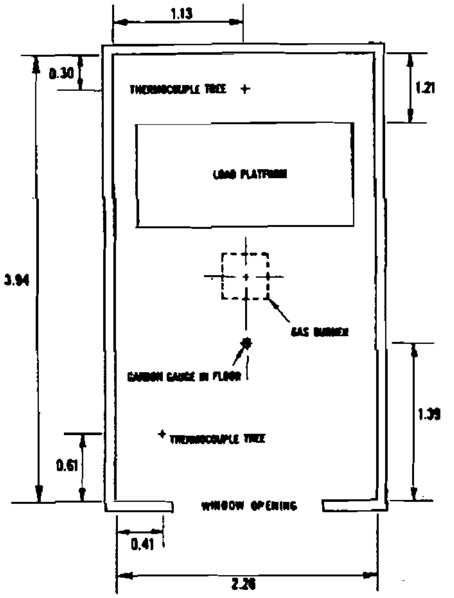
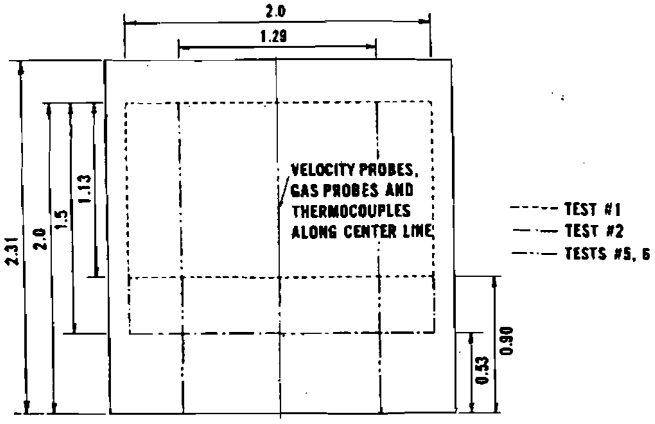


Figure 1. Plan view of experimental room (window opening dimensions indicated in Figure 2).

It was considered desirable to make accurate window opening plane measurements of mass and heat flow. Since earlier work (on small, steady-state fires) [5,6] showed the desirability of closely spaced measuring points, 15 bidirectional velocity probes, with companion thermocouples, were located equally-spaced along the vertical centerline. Two gas sampling probes were also located along the upper part of the opening centerline.

The tests in the furniture calorimeter [1,2] made use of a gas burner simulating a wastebasket fire as the ignition source. Because of practical difficulties in installing that burner in the test room, actual



ALL DIMENSIONS IN METERS

Figure 2. Elevation of experimental room.

wastebasket ignition was used. This involved a 285 g polyethylene basket filled with 390 g of milk cartons [7].

The room was conditioned prior to testing by some burner fires whereby the paper facing was burned off the wallboard and the surface moisture driven off. The room was allowed to cool overnight after conditioning and between tests.

The test furniture, specimens F21 and F31, were constructed for the prior work [1]. They comprised a 28.3 kg armchair (F21) and a similar 40.0 kg loveseat (F31). Both were of conventional wood frame construction and used polyurethane foam padding, made to minimum California State flammability requirements, and polyolefin fabric. Additional specimen details were given in [1]. A single piece of test furniture and the igniting wastebasket were the only combustibles in the test room.

Four tests were conducted, listed in Table 1. The soffit depth of the window opening was the same in all cases (Figure 2). For tests 1 and 2 the opening height (and therefore the ventilation parameter $A\sqrt{h}$) only was varied. For test 6 the same $A\sqrt{h}$ was retained but the shape of the opening was changed, compared to Test 2. Test 5 resembled Test 6 except that the smaller specimen was used. Thus for specimen type, ventilation factor, and opening aspect ratio, a pair of tests each was provided where these variables were singly varied, the other two being held constant.

Table 1. Tests conducted.

Test	Chair	Soffit depth (m)	Opening width (m)	Opening height (m)	$A\sqrt{h}$ $(m^{5/2})$
1	F31	0.31	2.0	1.13	2.43
2	F31	0.31	2.0	1.50	3.65
5	F21	0.31	1.29	2.00	3.65
6	F31	0.31	1.29	2.00	3.65

EXPERIMENTAL RESULTS

Gas Flows

Initial calibrations with gas burner flows showed adequate agreement, to within 10-15%, of window mass inflows and outflows, after an initial transient period of about 30 s. Similarly, during the final, smoldering stages of the furniture fires a reasonable mass balance was obtained. During peak burning periods in the upholstered furniture tests such agreement, however, was not obtained. The data show many-fold more inflow than outflow, at some times even zero outflow. Since a thorough checking of instrumentation did not show any malfunctions, a close visual observation was made of the fire during one of the later tests (photographic records were not distinct enough to reveal the flow structure). Figure 3 shows a representation of the visible flow pattern. The bottom portion of the opening was not smoky and was presumed to be inflow. The top portion, however, did not show the "inverted-weir" flows customarily associated with room fire flows. Instead, outflows were localized along opening side edges and top edge. In each of these regions the flow curled around the opening edge. The middle portion appeared stagnant and did not move with the edge and top flows. This is then seen to be the reason for the lack of mass balance—the probes were located only along the centerline.

Steady-state flow studies generally involved a horizontal traverse of probes through the opening [5,6]. This permits any lateral deviations to be properly accounted for. In a furniture fire, however, such a traverse is not feasible; more extensive fixed probe instrumentation is also impractical. Yet there are room fires where a successful mass balance is obtained [8]. These generally differ from the present series in: (a) slower rate of fire buildup; (b) tall, narrow rather than short, broad ventilation openings; (c) lower compartment temperatures,

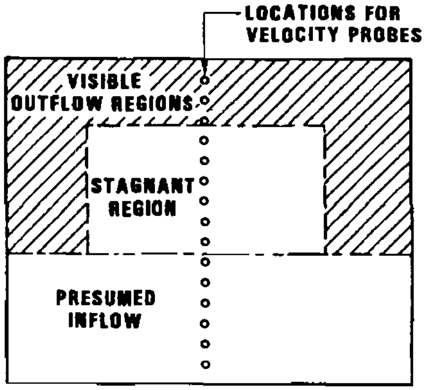


Figure 3. Visual observations of flow at the window opening.

generally short of flashover. Theoretical considerations suggest that outflow may slightly exceed inflow due to the contributions of fuel pyrolyzed mass and due to initial gas expansion. Fang [9] recorded outflow/inflow ratios of over 3 in some furnished room fire tests. To estimate the effects of known error sources, an approximate expression for the flows is needed. Conventionally the air mass flow rate is taken [3] as $m_a \cong 0.5\, A \sqrt{h}$. For non-planar flows, such as seen here, an expression of this form cannot be exact. Nonetheless, in the absence of a better expression, this relationship should at least indicate the correct trends. For the present tests these approximate flows are 1.2 *kg/s* for test 1 and 1.8 *kg/s* for the remaining ones. The gas expansion is $d(\varrho V)/dt$. The peak value of this term for the present tests is about 0.03 *kg/s*. The peak fuel release rates were in the vicinity of 0.1 *kg/s*. Finally, there is the possibility of flow error due to streamline angle effect. This effect stems from the fact that air inflow is largely horizontal, whereas the outflow has a strong vertical component due to buoyancy. A measurement error results since the velocity probes indicate the vector-sum, rather than the horizontal component alone. Steady-state errors of about 20% can be expected from this source alone [5,9]. It bears emphasis that all three factors discussed above would contribute to an indicated relative outflow *excess*, whereas the measured quantities show an outflow *shortage*. Thus, the explanation is seen to lie in the fluid flow pattern, shown in Figure 3, and not in the other effects described above.

The implication of these findings is that until the limitations of inverted-weir flow validity are understood, real compartment fires should not be presumed to necessarily exhibit this type of flow. Measurements of mass or heat flows at a window plane, based on center-line readings will thus not give useful results. The quantity of most interest, the heat release rate, can satisfactorily be determined from measurements in the exhaust system. These measurements indicate total values of heat release from both inside the room and from the combustion taking place outside, if any, in the plume formed above the window. A method for separation of these two quantities with useful accuracy does not seem to be available. Such plume burning was not of major importance in the present study since the fires did not reach a ventilation-limited burning, which is required for significant window plume combustion.

Heat Fluxes

The radiant heat fluxes, measured at the location shown in Figure 1 with Gardon type gages, are plotted in Figure 4. Specimen F21, being smaller than F31, showed consistently lower heat fluxes. The three tests with F31 showed essentially identical behavior. The peak was slightly lower in Test 1 and the duration was slightly longer in Test 6. These deviations are minor and significance is not attached to them. Flashover was reached in all tests; it is indicated on Figure 4 at the 20 kW/m² level.

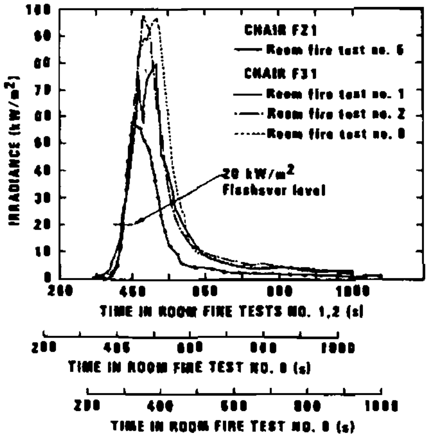


Figure 4. Irradiance measured at floor level.

Table 2. Results of measurements.

Test	Stoich. $\dot{q}$ (kW)	Peak $\dot{q}^a$ (kW)	Peak Floor Irrad. (kW/m²)	Flashover[b] Time (s)	Flashover[b] Measured $\dot{q}$ (kW)	Flashover $\dot{q}$ ÷ Stoich. $\dot{q}$ (–)	Peak $\dot{q}$ ÷ Stoich. $\dot{q}$ (–)
1	3650	2490	79	373	1200	0.33	0.68
2	5480	3550	99	377	1940	0.35	0.65
5	5480	2260	58	302	1700	0.31	0.42
6	5480	2660	97	410	1390	0.25	0.49

[a] – determined from oxygen consumption measurements in the exhaust hood.
[b] – taken as occurring when floor irradiance reaches a value of 20 kW/m².

Heat Release Rate

Heat release results are summarized in Table 2. The values of stoichiometric heat release rate can be properly computed using $\dot{m}_a \cong 0.5\,A\sqrt{h}$, since stoichiometric burning corresponds to a fully-choked window flow condition. In such a case the simplified flow expression is applicable. The expression for the stoichiometric (change point from fuel-limited to ventilation-limited) heat release rate is then given by [3]

$$\dot{q}_{stoich} = 13.1 \times 10^3 \left(\frac{kJ}{kg\ O_2}\right) \cdot 0.232 \left(\frac{kg\ O_2}{kg\ air}\right) \cdot 0.5\,A\sqrt{h} \left(\frac{kg\ air}{s}\right)$$

$$= 1520\,A\sqrt{h} \quad (kJ/s)$$

where A is the ventilation opening (m²), h is its height (m), and the oxygen consumption factor (13.1×10^3 $kJ/kg\ O_2$) is discussed in [4]. The $\dot{q}$ peak is as determined by the measurements in the exhaust stack. The time for flashover was determined according to the measurement of 20 kW/m² flux value at the floor. The uncertainty for these figures can be determined by considering that the rate of rise of $\dot{q}$ during the time when flashover occurred was approximately 33 kW/s for all four tests. Since the data were recorded at 10 s intervals, it is reasonable to assume an uncertainty corresponding to a 10 s interval, or ± 330 kW. The experimentally determined ratios of flashover $\dot{q}$ to $\dot{q}_{stoich}$ are seen from Table 2 to be 0.25 to 0.35. Finally, peak $(\dot{q}/\dot{q}_{stoich})$ values are seen to lie well below 1.0, which indicates that a ventilation-limited burning regime was not reached.

Influence of the Room on the Burning Rate

Figure 5 shows the heat release rates for chair F21—two replicate tests in the furniture calorimeter, along with the room test 5. Since the ignition times using the wastebasket were not identical to those using the simulation burner, the curves have been time-shifted to overlay during the initial rise period. The heat release rate in the room fire is not significantly enhanced even after flashover. The approximately 10% higher peak in the room fire must be considered in light of the accompanying 10% or so increased peak width. Since the total combustible mass was the same in the room fire as in the furniture calorimeter, if actually faster burning was recorded, the room fire peak should be narrower. That it is not, suggests measurement scatter rather than actual radiative augmentation.

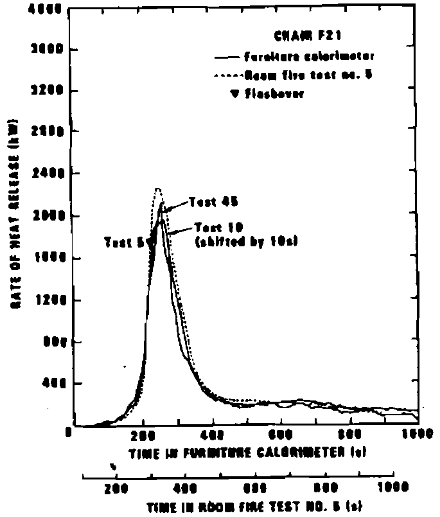


Figure 5. Rate of heat release for chair F21.

Figure 6 shows similar results for chair F31. Two of the room fire peaks are lower and one is higher than the corresponding furniture calorimeter tests. If there were no enclosure effects, the expected peak reading would be the furniture calorimeter value, 2890 kW, with the uncertainty estimated above, ± 330 kW. The measured values of 2490, 2660 and 3550 exceed only slightly the expected range of 2560 to 3220 kW. Based on the test room configuration, there is no reason to expect that test 2 would result in an enhanced burning rate while tests 1 and 6 would show a decrease. The ventilation opening effect, if any, should be more dependent on $A\sqrt{h}$ than on the aspect ratio. Yet, comparing

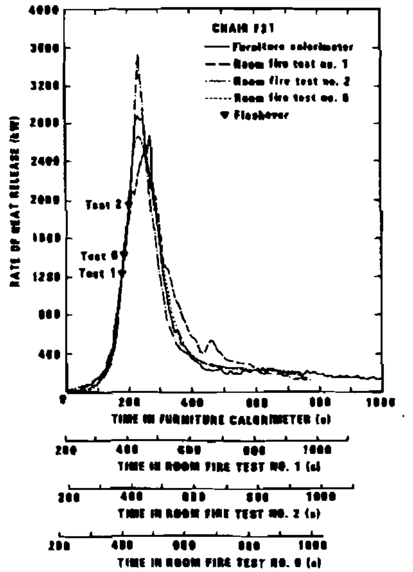


Figure 6. Rate of heat release for chair F31 (loveseat).

between tests 1-6 and tests 2-6 would suggest the opposite, thus lending credence to a random variation hypothesis. The physical interpretation is that with the type of furniture tested the flames are sufficiently radiatively thick to be insensitive to external heat flux variations.

FLASHOVER PREDICTIONS

Flashover in the course of a fire occurs when the room "becomes filled with flame." It can be quantitatively described as corresponding to a gas temperature $T_f = 600\,°C$, or a floor irradiance $\dot{q}'' = 20$ kW/m² or possibly as a number of other related, though not necessarily identical occurrences. In an earlier study [3] it was pointed out that a simple rule could be established, based on dimensional analysis and data correlation, which states that flashover is reached when the heat release rate within a room exceeds 50% of the stochiometric burning rate. For natural convection through a window opening $\dot{m}_a \cong 0.5\, A\sqrt{h}$, giving the minimum heat release rate for flashover as

$$\dot{q}_{fo} = 750\, A\sqrt{h} \quad (kW) \tag{1}$$

The above expression does not take into account varying heat losses due to room wall size or property variations. For materials of known thermal properties, the wall losses are not difficult to quantify. A simple calculational procedure was recently proposed [10] which to good precision allows closed-form expressions for wall losses to be used. Consider the following wall properties, appropriate for gypsum wallboard:

$$k\rho C = 112800. \qquad (J^2 \cdot s^{-1} \cdot m^{-4} \cdot °C^{-2})$$
$$L/k = 0.235 \qquad (m^2 \cdot °C \cdot W^{-1})$$

Also, consider that $T_\infty = 25\,°C$ and the opening height is 2 m (for radiation loss calculations only; this is not a very sensitive effect). Further, let the time scale for wall heating be set as $t = 100$ s, appropriate for an upholstered furniture fire. Finally, assume, conservatively, that the unmixed fuel fraction is zero. The procedure given in [10] relates the fire temperature, T_f, as a function of heat generated, $\dot{q}$, and room geometric and thermal properties. Inserting the above values and letting $T_f = 600\,°C$ permits a solution for $\dot{q}$ at flashover ($\dot{q}_{fo}$) to be obtained:

$$\frac{600\text{-}25}{1725\text{-}25} = \left[1 + 0.51 \ln \frac{\dot{q}_{fo}}{1.5\, A\sqrt{h}}\right] \left[1 - 0.94 \exp\left(-33\left[\frac{A\sqrt{h}}{A_w}\right]^{2/3}\right)\right] \cdot \left[1 - 0.92 \exp\left(-11.9\left[\frac{A\sqrt{h}}{A_w}\right]^{0.6}\right)\right] \cdot 0.83 \tag{2}$$

This can be solved in the form

$$\frac{\dot{q}_{fo}}{A\sqrt{h}} = f\left(\frac{A_w}{A\sqrt{h}}\right) \tag{2'}$$

The results are shown in Figure 7.

Recently a number of other simplified expressions have been advanced for predicting room flashover. These include the work by Thomas [11], Hägglund [12], McCaffrey [13], and Peacock [14]. The expression deduced by Thomas [11] is

$$\frac{\dot{q}_{fo}}{A\sqrt{h}} = 378 + 7.8\,\frac{A_w}{A\sqrt{h}} \tag{3}$$

Hägglund's recommendation [12] can be expressed as

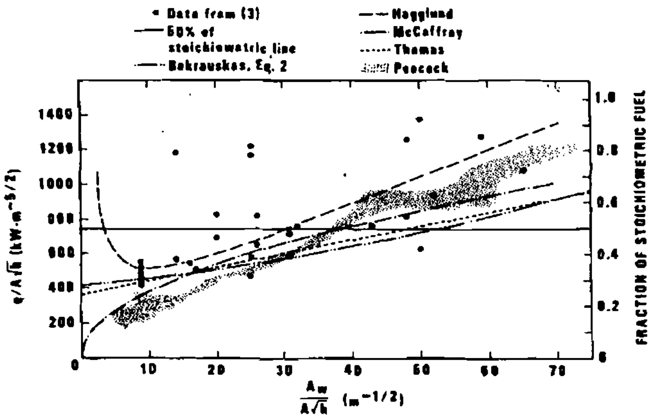


Figure 7. The effect of room wall area (gypsum walls) on the heat required for flashover.

$$\frac{\dot{q}_{fo}}{A\sqrt{h}} = 1050\,\frac{A_w}{A\sqrt{h}}\left[\frac{1.2}{A_w/A\sqrt{h}} + 0.247\right]^{3} \qquad (4)$$

McCaffrey's [13] expression, evaluated for gypsum wallboard walls, is

$$\frac{\dot{q}_{fo}}{A\sqrt{h}} = 111\left[\frac{A_w}{A\sqrt{h}}\right]^{1/2} \qquad (5)$$

Peacock [14] did not derive a continuous expression, but rather solved a number of specific cases. His trends are indicated in Figure 7 as a striped area.

The solid points in Figure 7 indicate the data originally analyzed in [3]. A constant factor expression provides, obviously, a less good fit than models where $A_w/A\sqrt{h}$ is taken into account. For much of the domain, the methods of Babrauskas, Thomas, Hägglund, and McCaffrey give rather similar results. The findings of Peacock, however, for $A_w/A\sqrt{h} \leqslant 30$ are significantly lower than either the experimental points or any of the other functions. This can be attributed largely to the choice of a low value for flashover T_f and a low plume entrainment coefficient in [14]. The equations of both Hägglund and McCaffrey show asymptote anomalies. While normal rooms will rarely have $A_w/A\sqrt{h} < 8$, the ratio $q/A\sqrt{h}$ should not, in fact go to either zero or infinity, as $A_w/A\sqrt{h} \rightarrow 0$ represents not necessarily very small walls but merely well-insulating ones. The expressions of Thomas and Babrauskas both meet this requirement. Since the analysis is approximate anyway, there appears to be no reason to not use Thomas' simpler, linear expression. For design purposes a slightly conservative representation of data—rather than a straight mean—is usually desired. It can be seen in Figure 7 that both Equation 2 and Equation 3 show this desirable property.

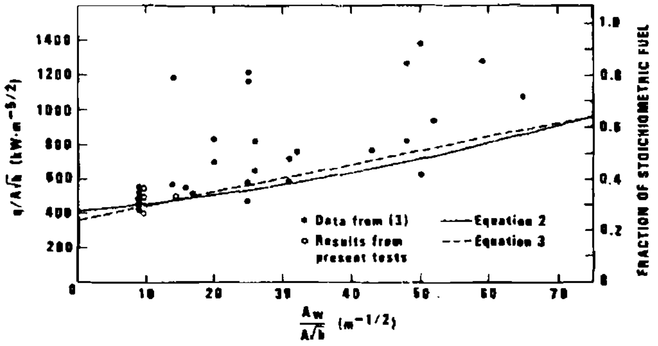


Figure 8. Results from present tests compared to theoretical expressions.

Shown in Figure 8 are results for the four tests of the present experimental program. It is again demonstrated that Equation 2 provides a suitable predictor for flashover and, similarly, that Equation 3 is a useful linear approximation.

CONCLUSIONS

The validity of open-burning measurements for determining preflashover burning rates in room fires has been successfully verified for typical upholstered furniture specimens.

Post-flashover burning of these upholstered furniture items was also seen not to be significantly different from the open-burning rate, for fires which are fuel-limited. Fires with ventilation control by definition show a lower heat release rate within the room. Experimental measurements are badly needed in this area.

The typical test arrangement of velocity probes spaced up and down along the ventilation opening centerline was found to lead to serious errors in computed mass and heat flows. Data taken in the exhaust system collecting the fire products did provide for satisfactory heat release measurements. A method is still lacking which could adequately separate the outside plume combustion heat from that released within the fire room itself.

Various relations for predicting flashover were examined in light of the present data, supplementing an earlier analysis. The relationship

$$\frac{\dot{q}_{fo}}{A\sqrt{h}} = 378 + 7.8\,\frac{A_w}{A\sqrt{h}} \qquad (3)$$

proposed by Thomas, was identified as the most useful relationship, taking into account wall area and properties, when the simple relationship

$$\frac{\dot{q}_{fo}}{A\sqrt{h}} = 750$$

is not sufficient. Equation 3 may not be applicable for fires with a very slow build-up rate or for wall materials substantially different from gypsum wallboard, in which case Equation 2 should be used.

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NOMENCLATURE

A	Area of ventilation opening (m^2)
A_w	Area of walls (m^2)
C	Heat capacity ($J \cdot kg^{-1} - K^{-1}$)
h	Height of ventilation opening (m)
k	Thermal conductivity ($W - m^{-1} - K^{-1}$)
L	Thickness (m)
$\dot{m}_a$	Air flow rate ($kg - s^{-1}$)
$\dot{q}$	Heat release rate (kW)
$\dot{q}_{fo}$	Heat release rate at flashover (kW)
q_{stoich}	Stoichiometric heat release rate (kW)
t	Time (s)
T_f	Gas temperature (°C)
T_∞	Ambient temperature (°C)
V	Volume (m^3)
ρ	Density ($kg \cdot m^{-3}$)

REFERENCES

1. Babrauskas, V., Lawson, J. R., Walton, W. D., Twilley, W. H., "Upholstered Furniture Heat Release Rates Measured with a Furniture Calorimeter," Nat. Bur. Stand (U.S.), NBSIR 82-2604 (1982).
2. Babrauskas, V., "Upholstered Furniture Heat Release Rates: Measurements and Estimation," *J. of Fire Sciences, 1*, pp. 9-32 (1983).
3. Babrauskas, V., "Estimating Room Flashover Potential," *Fire Technology, 16*, pp. 94-103, 112 (1980).
4. Huggett, C., "Estimation of Rate of Heat Release by Means of Oxygen Consumption," *Fire and Materials, 4*, pp. 61-65 (1980).
5. Tu, K-M, Babrauskas, V., "The Calibration of a Burn Room for Fire Tests on Furnishings," Nat. Bur. Stand. (U.S.), Tech. Note 981 (1978).
6. Steckler, K. D., Quintiere, J. G., Rinkinen, W. J., "Flow Induced by Fire in a Compartment," pp. 913-920 in *Nineteenth Symp. (Intl.) on Combustion*. The Combustion Institute (1982).
7. Babrauskas, V., "Will the Second Item Ignite?" *Fire Safety J. 4*, pp. 281-292 (1981/82).
8. Quintiere, J. G., McCaffrey, B. J., "The Burning of Wood and Plastic Cribs in an Enclosure," Vol. 1, Nat. Bur. Stand. (U.S.) NBSIR 80-[illegible] (1980).
9. Fang, J. B., "Static Pressures Produced by Room Fires," Nat. Bur[illegible] (U.S.), NBSIR 80-1984.
10. Babrauskas, V., "A Closed-Form Approximation for Post-[illegible] partment Fire Temperatures," *Fire Safety J. 4*, pp. 63-[illegible]
11. Thomas, P. H., "Testing Products and Materials for [illegible] Flashover in Rooms," *Fire and Materials, 5*, pp. 103-[illegible]
12. Hägglund, B., "Estimating Flashover Potential in Residential Rooms," (FOA Rapport C 20369-A3). Forsvarets Forskningsanstalt, Stockholm (1980).
13. McCaffrey, B. J., Quintiere, J. G., Harkleroad, M. F., "Estimating Room Temperatures and the Likelihood of Flashover Using Fire Test Data Correlations," *Fire Technology, 17*, pp. 98-119 (1981).
14. Peacock, R. D., Breese, J. N., "Computer Fire Modeling for the Prediction of Flashover," Nat. Bur. Stand. (U.S.), NBSIR 82-2516 (1982).

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RESIDENTIAL UPHOLSTERED FURNITURE IN THE UNITED STATES AND FIRE HAZARD

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ABSTRACT

Full scale fire tests were performed on three items of upholstered furniture used in US residential applications. The items were virtually identical, except that two of them contained foam padding that complied with the California TB 117 requirements and one did not. In all three cases, the furniture was easily ignited by the effect of a small open flame in the middle of the seat and released heat sufficiently fast (well over 2 MW) to cause flashover in the fire test room. The major fire performance difference between the CA TB 117 foam products and the standard foam product was the fact that a slightly more intense igniting flame was needed for the former. For comparison purposes, an alternative commercial item of upholstered furniture, which used well fire-retarded foam, was also tested; it easily resisted ignition by small open flames.

INTRODUCTION

The fire performance of an individual furnishing item is often crucial in determining whether a room becomes untenable in a fire, thus resulting in fire fatalities [1-2]. Back in the 1970s it was established that upholstered furniture represented a potentially serious concern: a single item can yield a fire severe enough to engulf a whole room and take it to flashover. As a consequence of this, in the USA, the Boston Fire Department and the California Bureau of Home Furnishings (CBHF), independently, developed flaming ignition fire tests for full scale items of upholstered furniture, intended for medium or high risk applications, the most famous being the first edition of California Technical Bulletin 133 (CA TB 133) [3], which had as its principal pass/fail criterion the temperature increase in the test room, which can be correlated with heat release. The test was initially intended to be a "low-tech" tool for qualitative use by manufacturers. In other words, the simple application of the ignition source, with little instrumentation would permit a test user to assess whether the chair would burn vigorously or not. Unfortunately, the output was not usable for more comprehensive assessments of fire safety.

CA TB 133 was then modified to require heat release output and it has since been used for regulation in several US states (beyond just California) and in codes. In fact, NFPA 101 [4], Life Safety Code, NFPA 301 [5], Life Safety Code for Ships, and the International Fire Code, IFC, [6] all require ASTM E 1537 [7], functionally identical. It is also used extensively for specifications, particularly in the area of contract furniture, since the early 1990s. However, it must be noted that the pass-fail criteria for upholstered furniture in the codes is milder than that in CA TB 133: 250 kW peak rate of heat release and 40 MJ total heat released, as opposed to 80 kW and 20 MJ. However, that difference is often not that critical as the test method commonly acts functionally as a "padding ignition test": if the padding becomes properly ignited the chair or sofa fails the test.

CBHF also developed a test for mattresses, which is analogous (but not identical) to CA TB 133: CA TB 129 [8]. However, this test was never used for regulations by either the state of California, or any other US state (although it is also included in NFPA 101, NFPA 301 and the IFC, as ASTM E 1590 [9], again functionally identical to CA TB 129, just like CA TB 133 is to ASTM E 1537). CA TB 129/ASTM E 1590 involves exposure of mattresses for 3 min to an 18 kW propane gas flame. Again, the codes are more lenient than the original test method: 250 kW and 40 MJ as opposed to 100 kW and 25 MJ. Once more, of course, that difference is often not that critical as the test method commonly acts functionally as a "padding ignition test": if the padding becomes properly ignited the mattress fails the test. In 2003 CBHF developed a new mattress test, CA TB 603 [10], which is of a similar type but significantly less severe than CA TB 129. CA TB 603 but will be used as a regulatory tool for **all mattresses** sold in the state starting in 2005 (including all residential mattresses). However, mattress foams will no longer be required to meet any fire test themselves.

In the United Kingdom, a different (and very simple) test was the first serious attempt at developing a flaming ignition standard for upholstered furniture systems: British Standard (BS 5852 [11]). This test uses a variety of wood cribs, and it tests a combination of fabric and filling, made up into two standard cushions: bottom and back. The wood cribs in BS 5852 range from # 4 (weighing 8.5 g), through # 5 (weighing 17 g) to # 7 (weighing 126 g). Less severe ignition sources (originally included in part 1 of BS 5852) address smokers' materials: cigarettes and butane flames simulating matches. An empirical study showed that the "rankings" resulting from testing fabric/foam combinations in this test correlated well with those that could be obtained from using the cone calorimeter at 25 kW/m^2 [12]. The cone calorimeter [13] has been shown to be an effective predictor of whether a product will cause flashover on its own [2], and it is particularly effective when used for upholstery composites with the ASTM E1474 protocol [14]. Following its initial adoption, BS 5852 was modified somewhat, so that testing for qualification is now done effectively on separate items. Fillings are qualified when tested under a "standard" flame retarded polyester fabric and fabrics are qualified when tested over a filling deemed acceptable. Thus, it is not required to test the system actually proposed for use, which makes testing more accessible to materials manufacturers (and less costly for them), as they need not test the large variety of potential finished systems. The British government issued the Furniture and Furnishings Fire Regulations Act in 1988, which requires all fabric and polyurethane foams used in the construction of upholstered furniture to meet BS 5852, crib #5 fire test requirements, and all filling materials in mattresses, including cot mattresses, to meet the same regulations (following the 1989 amendments). In other words, no filling or padding materials sold for use in upholstered furniture or in mattresses in the United Kingdom is permitted to ignite and spread flame when exposed to a crib # 5, while covered by a standard fire retarded polyester fabric (the standard fabric does not actually protect from ignition).

Requirements to protect the public from smoldering fires have been in effect both in the USA and in the UK for a large number of years. In the USA, residential upholstered furniture components generally meet a voluntary smoldering ignition standard nationwide, as administered by the Upholstered Furniture Action Council, since the late 1970s, with mandatory requirements in place in California (where small flame ignition requirements also exist[a]) and in some other jurisdictions. All mattress and mattress pads (including residential) are required, since 1972, to comply with 16 CFR Part 1632 [15]: a smoldering ignition (by cigarettes) test method. This test method has been instrumental in heavily decreasing (and virtually eliminating) cases where a mattress undergoes flaming combustion resulting from ignition by a smoldering cigarette, usually by replacing cellulosic padding or filling materials (such as cotton) with non smoldering plastic materials. However, there are no requirements for flaming ignition of upholstered furniture or of mattresses or mattress pads, or of their components, in the USA, other than the above-mentioned requirements for ASTM E 1537, or ASTM E 1590 as applicable, in some high risk applications in codes.

Data presented in Figure 1 shows that the fire fatalities in the UK are much lower than those in the US for fires where upholstered furniture[b] is the item first ignited (fire fatalities from fires where the item first ignited is a mattress or bedding in the UK are also shown). The decreases are (to a significant extent associated with the changes in fire safety requirements for upholstery in the UK). The US Consumer Product Safety Commission (CPSC) has changed the way in which it assesses fire loss figures since 1998, and they are not comparable with earlier figures. Table 1 shows a comparison of fire fatalities from fires starting in upholstered furniture in the UK and the US in 1988 (just when the UK regulation was introduced), then in 1997 (when the last reliable US statistics exist) and in 2002 (for the UK only) [16, 17].

Table 1 [16, 17] clearly shows that the decrease in fire fatalities per capita in the UK was very fast over the first 10 years following the UK fire safety regulations, and is continuing. The US fire fatality rate (which was not much larger than the UK one in 1988) has decreased much more slowly. Table 2 shows that the UK fire losses are almost completely associated with old furniture, since there are so few fires where the material first ignited is "combustion-modified foam upholstery". Unfortunately, in more recent years UK furniture also contains padding materials that are not foamed and they exhibit much poorer fire performance, something indicated by an increased tendency for fires, although they usually don't lead to fire fatalities.

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[a] In fact, upholstered furniture has always been able to be sold (and continues to be able to be sold) in California without meeting small open flame requirements, if it is clearly labeled as such.

[b] The categories included in these statistics are: furniture (not upholstered), combustion-modified foam upholstery, other foam upholstery and other upholstery, covers.

Table 1. Comparison of Fire Fatalities per Million Population in the United Kingdom and in the US for Fires Where Upholstered Furniture is the Item First Ignited

Year	UK Population (millions)	US Population (millions)	Fire Fatalities per Million UK	Fire Fatalities per Million US
1988	57.0	245.8	3.4	3.9
1997	58.9	267.8	1.5	2.5
2002	60.2	287.6	1.1	

Table 2. Fire Losses in the United Kingdom When the Material First Ignited is "Combustion-Modified Foam Upholstery"

Year	Fires	Fire Fatalities	Fire Injuries
1994	0	0	0
1995	Not available	Not available	Not available
1996	1	0	0
1997	7	0	5
1998	14	0	2
1999	8	1	1
2000	13	0	3
2001	41	1	9
2002	58	0	19
Total	142	2	39

It should be noted that between 1988 and 1997 (the years where the UK regulation on upholstery was issued and the latest year for which reliable data from both countries are available), fatalities in UK fires where an upholstered furniture item was the item first ignited, decreased by 53.4%, while US fire fatalities decreased much less: 38.7% (even though the opportunity for improvement was greater since many more people died in such fires). The widespread, and growing use, of smoke detectors is probably one of the main reasons for the US improvements, as there have been no requirement for changes in the composition of upholstery or mattress materials in recent years.

In the UK, the Department of Trade and Industry commissioned a study to look at the effects of the 1988 legislation in terms of lives saved, decreased number of injuries and economic impact [18] Some of the key improvements are shown in Table 3, based on an official UK government publication, for upholstered furniture only. The study indicates that 710 lives (and over £5 billion) were saved over a 10 year period, in spite of the relatively low smoke detector penetration into the UK. In fact, a follow-up UK study shows that neither smoke detector penetration nor the changes in smoking patterns can explain the improvement in fire losses [19]. A particularly important societal aspect of the UK study has been the economic analysis, included the cost to industry (which, by and large, was not passed on to the consumer) of developing and selling products with greatly improved fire performance.

Table 3 - Benefits Resulting From UK Upholstery Regulations up to 1997			
Benefit measure	Annual benefit 1992	Annual benefit 1997	Cumulative benefit 1988-1997
Number of dwelling fires	3,715	8,769	42,754
Total lives saved	169	362	1,856
Lives saved for upholstery as item first ignited	65	138	7,100
Total non-fatal injuries saved	1,548	3,315	17,000
Injuries saved for upholstery as item first ignited	526	1,126	5,774
Loss adjusted cost saving £m/yr	23	53	249
Final cost saving £m/yr	507	10,835	5,567
Total cost saving £m/yr	530	1,138	5,615

Note: the exchange rate between the UK £ and the US $ is ca. 1.8.

During a series of full-scale fire tests of 37 upholstered furniture items at the National Institute of Standards and Technology (NIST, then called National Bureau of Standards), it was found that furniture peak heat release rates ranged between 10 and 3,120 kW, as early as 1985 [20]. In fact, even mock-up full-scale chair tests can yield up to 1,460 kW [21]. Shortly thereafter, a similar range of peak heat release rates was found in a study of upholstered furniture by the State of California, together with NIST [22]. This is completely parallel to what is known about fire safe mattresses, as was described recently [23-24]. A complete study of such issues was published several years ago [25]. Thus, both the potential for poor fire performance of upholstered furniture and the feasibility of producing fire safe upholstered furniture has been known for many years.

This study presents the results of four full scale tests on upholstered furniture products, three of them made in the US and one made in the UK. The 3 US products (all large sectional sofas, functionally identical) originate from the same manufacturer: two of them contain foam that has been slightly fire retarded to comply with the California Technical Bulletin TB 117, while the foam contained in the third one was not fire retarded. The UK product contained foam that complied with the BS 5852 wood crib # 5 fire safety requirements and fabric that complied with the BS 5852 Ignition Source 1 (gas flame) fire safety requirements.

EXPERIMENTAL: TEST SERIES AND RESULTS

All four large scale tests were conducted in a standard "ASTM" room. The room dimensions are: 2.4 m x 3.7 m x 2.4 m (8 ft x 12 ft x 8 ft), with a door of 0.76 m (30 inches), centered on one of the short walls, and with an exhaust duct just outside the room. The test room volume was, thus: 21.75 m^3. The measurements made were those recommended for all large-scale heat release tests (for example by ASTM E 1537): heat release (by oxygen consumption calorimetry), smoke release in the duct and temperature measurements at various locations in the room and duct. Mass loss, heat fluxes and carbon oxide emission were also measured in the tests. The three sofas manufactured in the US were labeled US Sofa 1, US Sofa 2 and US Sofa 3 (where US Sofa 1 contained no CA TB 117 foam). The other sofa was labeled UK Sofa.

The ignition sources used for all tests were based on BS 5852. BS 5852 Ignition source 1 was used on all sofas, and the ignition was conducted in the seat section of one cushion (a section less prone to ignition than the side arm, the back or any edges). The ignition source is a butane gas flame with a 45 mL/min flow rate and a total application time of 20 s, simulating a match. Only US Sofa 1 ignited with this ignition source, and quickly developed a self-propagating fire. The other three sofas were then subjected to BS 5852 Ignition source 2, which is a butane gas flame with a 160 mL/min flow rate and a total application time of 40 s. Both the other US sofas ignited with this ignition source, and quickly developed a self-propagating fire. The UK sofa did not ignite with either ignition source.

Table 4 contains the summary information of the principal data of all large scale tests. Three of the 4 tests had to be extinguished soon after flashover to prevent damaging the test facility. At the time of extinguishment none of them had reached their maximum rate of heat release and the values of peak rate of heat release reported in Table 4 are those just before extinguishment. Similarly, the total smoke released is reported at 840 s, shortly after extinguishment for the US sofas, at the same time for all tests.

It is noteworthy that the time until a self-propagating fire was obtained differed only by a short time among the three US sofas, with the sofas containing foam complying with CA TB 117 taking just somewhat longer time to become a fire that went out of control. The sofa purchased in the UK did not ignite (with either ignition source) and the small flame (on the surface) gave a maximum rate of heat release of ca. 2 kW, and virtually unmeasurable amounts of smoke and mass loss. No graphs are presented of this data.

Table 4. Major Data from all 4 Large Scale Furniture Tests

	US Sofa 1	US Sofa 2	US Sofa 3	UK Sofa
Ignition Source	BS 5852 1	BS 5852 2	BS 5852 2	BS 5852 2
Extinguishment@ (s)	440	635	645	No ignition
Pk RHR (kW) (before extinguishment)	4,802	2,527	4,394	2
Time to flashover (s)	410	610	585	No ignition
Time to Pk RHR (s)	440	635	645	No ignition
Time before self-propagating fire (s)	335	520	495	No ignition
Total Heat Release @ 840 s (MJ)	292	254	359	No ignition
Flashover RHR in Test Room (kW)	1,000	1,000	1,000	1,000
Total Smoke Release @ 840 s (in m^2)	1,372	4,811	9,710	No ignition
Maximum Smoke Release (Code, in m^2)	1,000	1,000	1,000	1,000
Mass of Sofa (kg)	290	276	275	56
Mass Loss Before Extinguishment (kg)	6.1	4.6	9.1	No ignition
Maximum Toxic Smoke Concentration in Test Room Before Extinguishment (g/m^3) *	295	212	420	No ignition
Toxic Smoke Incapacitation Limit (g/m^3)	15	15	15	15
Time to Toxic Smoke Incapacitation Concentration in Test Room (s)	310	535	480	No ignition
Toxic Smoke Lethality Limit (g/m^3) *	30	30	30	30
Time to Toxic Smoke Lethality Concentration in Test Room (s)	340	570	525	No ignition

Note: * Based on smoke concentration for a 30 minute exposure period or the equivalent concentration-time product. This is calculated from the mass lost and the room volume and not from the measurements of toxic gases themselves, and includes all toxic species.

Figures 2-4 show the heat release obtained in the tests with each one of the three US sofas, both the rate of heat release (in kW) and the total heat released (in MJ). Figure 5 shows the rate of heat release curves for all three sofas together, compared with the values needed for flashover in the test room (namely 1 MW). Clearly all three sofas produce fires that go well beyond flashover fairly quickly. This is made clearer when the heat release rate data from all three sofas is plotted together, as in Figure 5.

Figures 6 and 7 show the smoke release and mass loss data for the same sofas. Smoke release in the room followed the pattern expected from the heat release data: since the upholstered furniture released abundant heat, it also caused abundant smoke obscuration [26]. For comparison purposes the total smoke obscuration limit used by the codes (International Building Code [IBC] (27), International Fire Code [IFC] (4), Life Safety Code [NFPA 101] (6) and Building Construction and Safety Code [NFPA 5000] (28)) for interior finish is being shown in Figure 6: 1,000 m^2. All three sofas release more smoke than interior finish (throughout the entire room) is allowed to release. Unfortunately, although heat release is predictable (at least to some extent) from small scale test data, smoke release is much less predictable, so full scale tests are needed to obtain that information [29-31].

DISCUSSION

The data pretty much speak for themselves. The protection afforded by using CA TB 117 foam is of little use, in that it does almost nothing else than delay ignition and the development of a self-propagating fire for a short period of time, while permitting a rapidly growing self-propagating fire to develop fairly quickly from a small ignition source. Such ignition sources are typically used by very young children when they play, while climbing through sofas or lying in bed. Once ignition has occurred and a self propagating fire has ensued, it is clear that rapid responses are needed. The low importance of ignition alone is highlighted by the conclusions of a European project (CBUF) investigating fire performance of upholstered furniture and mattresses, which does not even consider that "real ignition" has occurred until a product has released 50 kW [32]; in this work the fire is considered to become self-propagating once this 50 kW level has been reached. The UK sofa tested did not ignite with small readily available ignition sources.

It is necessary to consider the implications of the fire obtained on survivability. If tenability criteria are adopted (and Table 5 shows a set of criteria, based on the NIST fire model HAZARD I [33-34] and an ASTM standard on fire hazard assessment [35], criteria for incapacitation and lethality can be used for assessment in the fire test room.

Table 5. Tenability Criteria from HAZARD I and ASTM E 2280

Hazard	Incapacitation Criterion	Lethality Criterion
Smoke Toxicity Ct (g min/m^3)	450	900
Smoke Toxicity FED	0.5	1
CO Concentration (ppm min)	45,000	90,000
Convected Heat/Temperature (°C)	65	100
Radiated Heat/Heat Flux (kW min/m^2)	1.0	2.5
Smoke Obscuration	Extinction Coefficient (m^{-1}) x Visibility Distance (m) = 2 *	
* Lack of visibility has no direct health effects, but inhibits, or even prevents, safe escape or rescue.		

Notes: Smoke Toxicity Ct: concentration-time product of toxic gases. If exposure is 30 min, smoke toxicity criteria will be 15 g/m^3 for incapacitation and 30 g/m^3 for lethality. Smoke Toxicity FED: fractional effective dose of toxic insult required to cause lethality (if FED = 1).

Figure 8 shows the results of the application of the smoke toxicity criteria and Figure 9 shows the temperature data measured at the sofa itself, in one case.

In the tests described here, concentrations for incapacitation from smoke toxicity exposure (as shown above in Table 4) occur after just over 5 minutes with the sofa that has non fire retarded foam and a little bit later with the other sofas. In each case, concentrations for lethality from smoke toxicity exposure follow very shortly thereafter. Sofa temperatures exceed

65 °C at the cushions away from the ignition source within 5-7 min for the sofa with non FR foam. Clearly, both criteria quickly lead to untenable situations before a child or a sleeping adult is likely to react or help is likely to arrive. Of course, victims die only once, and it would actually be necessary to assess partial effects from each incapacitating criterion and combine them.

CONCLUSIONS

(a) Residential upholstered furniture in the US often has very poor fire performance.

(b) Corresponding residential upholstered furniture in the UK has adequate fire performance, including excellent ignition performance.

(c) The technology exists in the US (just like in the UK) to make upholstered furniture with excellent fire performance.

(d) Fire safety regulations addressing open flame ignition, exists in the UK.

(e) Fire safety of contract upholstered furniture in the US is governed by codes and specifications, but only for some institutional environments.

(f) The use of appropriately fire-safe upholstered furniture in the US would result in considerable decreases in fire losses and probably economic savings (since that has occurred in the UK).

REFERENCES

[1] Hirschler, M.M., "Fire Tests and Interior Furnishings", in *Fire and Flammability of Furnishings and Contents of Buildings*, ASTM STP 1233, Fowell, A.J., Ed., American Society for Testing and Materials, Philadelphia, PA, 1994; pp. 7-31.

[2] Hirschler, M.M., "Use of Heat Release Rate to Predict Whether Individual Furnishings Would Cause Self Propagating Fires", *Fire Safety J.*, 32, 273-296 (1999).

[3] *CA TB 133*, "Flammability Test Procedure for Seating Furniture for Use in Public Occupancies", State of California, Bureau of Home Furnishings and Thermal Insulation, North Highlands, CA, Technical Bulletin 133, January 1991.

[4] *NFPA 101*, "Life Safety Code", National Fire Protection Association, Quincy, MA.

[5] *NFPA 301*, "Code for Safety to Life from Fire on Merchant Vessels", National Fire Protection Association, Quincy, MA.

[6] *IFC*, "International Fire Code", International Code Council, Falls Church, VA.

[7] *ASTM E 1537*, "Standard Test Method for Fire Testing of Seating Upholstered Furniture", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

[8] *CA TB 129*, "Flammability Test Procedure for Mattresses for Use in Public Buildings", State of California, Bureau of Home Furnishings and Thermal Insulation, North Highlands, CA, Technical Bulletin 129, May 1992.

[9] *ASTM E 1590*, "Standard Test Method for Fire Testing of Mattresses", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

[10] *CA TB 603*, "Requirements and Test Procedure for Resistance of a Mattress/Box Springs Set to a Large Open Flame", State of California, Bureau of Home Furnishings and Thermal Insulation, North Highlands, CA, Technical Bulletin 129, January 2004.

[11] *BS 5852*, "Methods of test for the assessment of the ignitability of upholstered seating by smouldering and flaming ignition sources", British Standards Institution, 389 Chiswick High Road, London, W4 4AL, UK, 1990.

[12] Hirschler, M.M., and Smith, G.F., "Flammability of sets of fabric/foam combinations for use in upholstered furniture", *Fire Safety J.* 16, 13_31 (1990).

[13] *ASTM E 1354*, "Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

[14] *ASTM E 1474*, "Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

[15] *16 CFR Part 1632*, "Standard for the flammability of mattresses and mattress pads" (FF 4-72, amended), Code of Federal Regulations, Commercial Practices, Subchapter D: Flammable Fabrics Act Regulations, Vol. 16, part 1602-1632, January 1, 1992, pp. 617-636.

[16] Fire Statistics from the United Kingdom Office of the Deputy Prime Minister.

[17] Consumer Product Safety Commission US Fire Statistics on Fires Starting with Upholstery.

[18] *UK Government Consumer Safety Research*, "Effectiveness of the Furniture and Furnishings (Fire) (Safety) Regulations 1988", Consumer Affairs Directorate, Dept. Trade and Industry, London, UK, June 2000 [Research conducted by Professor Gary Stevens, Univ. of Surrey, Guildford, UK].

[19] Emsley, A.M., Lim, L. and Stevens, G., "International Fire Statistics and the Potential Benefits of Fire Counter-Measures", Flame Retardants 2002, February 5-6, 2002, London, pp. 23-32, Interscience Communications, London, UK, 2002.

[20] Babrauskas, V. and Krasny, J.F., "Fire Behavior of Upholstered Furniture - NBS Monograph 173", National Bureau of Standards, Gaithersburg, MD, 1985.

[21] Bukowski, R.W., "Investigation of the Effects of Heating and Air Conditioning on the Performance of Smoke Detectors in Mobile Homes – NBSIR 79-1915", National Bureau of Standards, Gaithersburg, MD, 1979.

[22] Parker, W.J., Tu, K.-M., Nurbakhsh, S. and Damant, G.H., "Furniture Flammability: an investigation of the California Technical Bulletin 133 test. Part III: Full scale chair burns", NISTIR 90-4375, Natl Inst. Stands Technology, Gaithersburg, MD, 1990.

[23] Hirschler, M.M., "Mattress/Bedding Fires: Statistics and Fire Data Associated with Recent Experience", Fire and Materials Conf., San Francisco, CA, Jan. 22-24, 2001, Interscience Communications, London, UK, pp. 129-140.

[24] Hirschler, M.M., "Flammability of Mattresses: Recent Fire Test Data and Implications", Business Communications Company Thirteenth Ann. Conference on Recent Advances in Flame Retardancy of Polymeric Materials, June 3-5, 2002, Stamford, CT, Ed. M. Lewin, pp. 280-925, Norwalk, CT, 2002.

[25] Krasny, J.F., Parker, W.J. and Babrauskas, V., "Fire Behavior of Upholstered Furniture and Mattresses", Noyes Publications, Park Ridge, NJ, 2000.

[26] Hirschler, M.M., "Heat release from plastic materials", Chapter 12 a, in "*Heat Release in Fires*", Elsevier, London, UK, Eds. V. Babrauskas and S.J. Grayson, 1992. pp. 375-422.

[27] *IFC*, "International Fire Code", International Code Council, Falls Church, VA.

[28] *NFPA 5000*, "Building Construction and Safety Code", National Fire Protection Association, Quincy, MA.

[29] Finley, G., Janssens, M.L., and Hirschler, M.M., "Room Fire Testing - Recent Experiences and Implications", Fire and Materials Conf., San Antonio, TX, Feb. 22-23, 1999, Interscience Communications, London, UK, pp. 83-94.

[30] Hirschler, M.M., and Janssens, M.L., "Smoke Obscuration Measurements in the NFPA 265 Room-Corner Test", Fire and Materials Conf., San Antonio, TX, Feb. 22-23, 1999, Interscience Communications, London, UK, pp. 179-198.

[31] Janssens, M.L., Dillon, S.E. and Hirschler, M.M., "Using the Cone Calorimeter as a Screening Tool for the NFPA 265 and NFPA 286 Room Test Procedures", Fire and Materials Conf., San Francisco, CA, Jan. 22-24, 2001, Interscience Communications, London, UK, pp. 529-540.

[32] CBUF Report, "Fire Safety of Upholstered Furniture - the final report on the CBUF research programme", Ed. B. Sundstrom, EUR 16477 EN, European Commission, Measurements and Testing Report, Contract No. 3478/1/0/196/11-BCR-DK(30), 1995, Interscience Communications, London, UK.

[33] Peacock, R.D., Jones, W.W., Bukowski, R.W. and Forney, C.L., "Technical reference Guide for the HAZARD I Fire Hazard Assessment Method, Version 1.1", NIST Handbook 146, Vol. II, Natl. Inst. Stand. Technol., Gaithersburg, MD (1991).

[34] Peacock, R.D., Jones, W.W., Forney, G.P., Portier, R.W., Reneke, P.A., Bukowski, R.W. and Klote, J.H., "An Update Guide for HAZARD I, Version 1.2", NISTIR 5410, Natl. Inst. Stand. Technol., Gaithersburg, MD (1994).

[35] *ASTM E 2280*, "Standard Guide for Fire Hazard Assessment of the Effect of Upholstered Seating Furniture Within Patient Rooms of Health Care Facilities", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

Figure 1 - UK Furniture & Bedding Fatalities (by Item First Ignited)

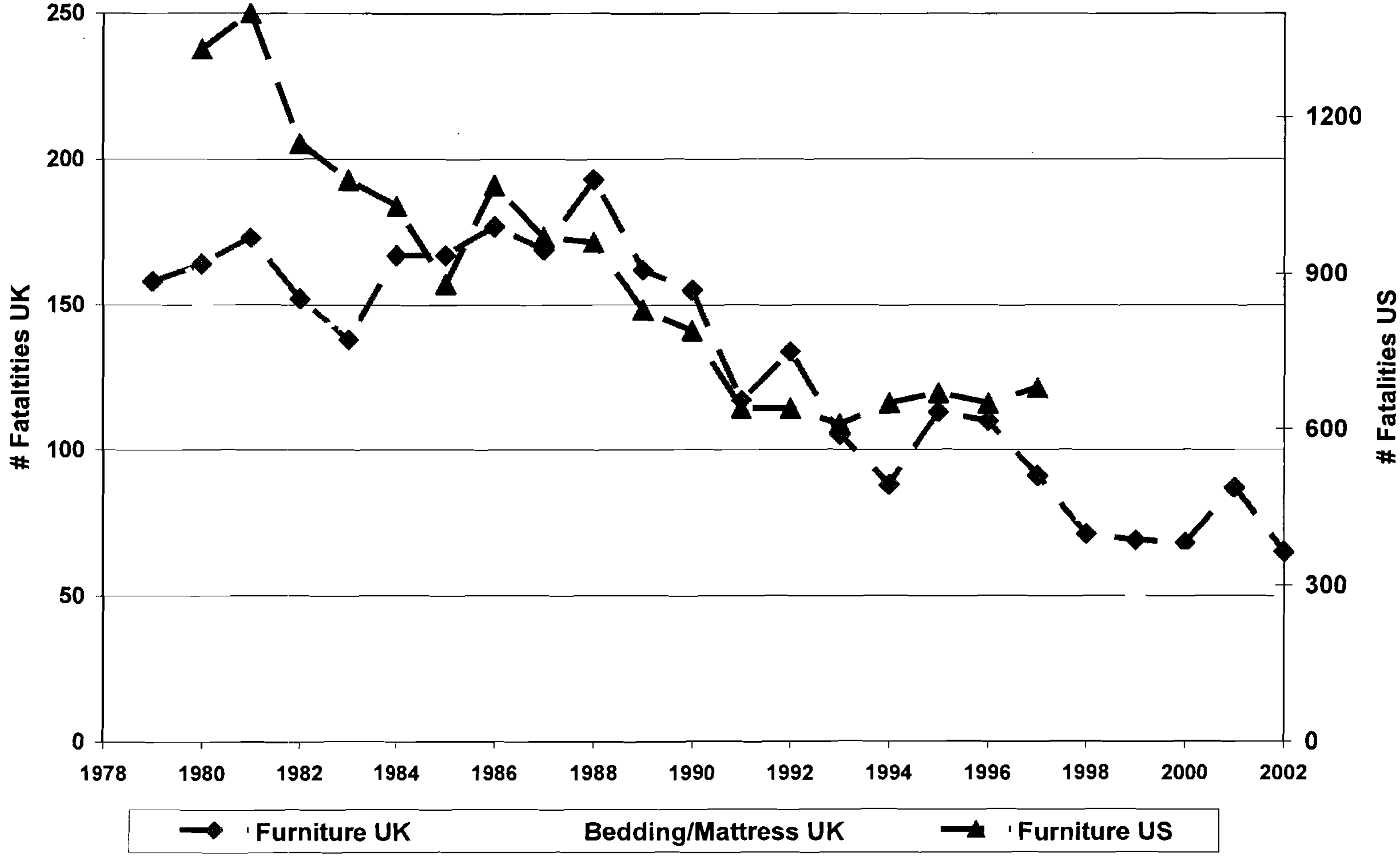


Figure 2: Rate of Heat Release Non CA TB 117 Foam Sofa

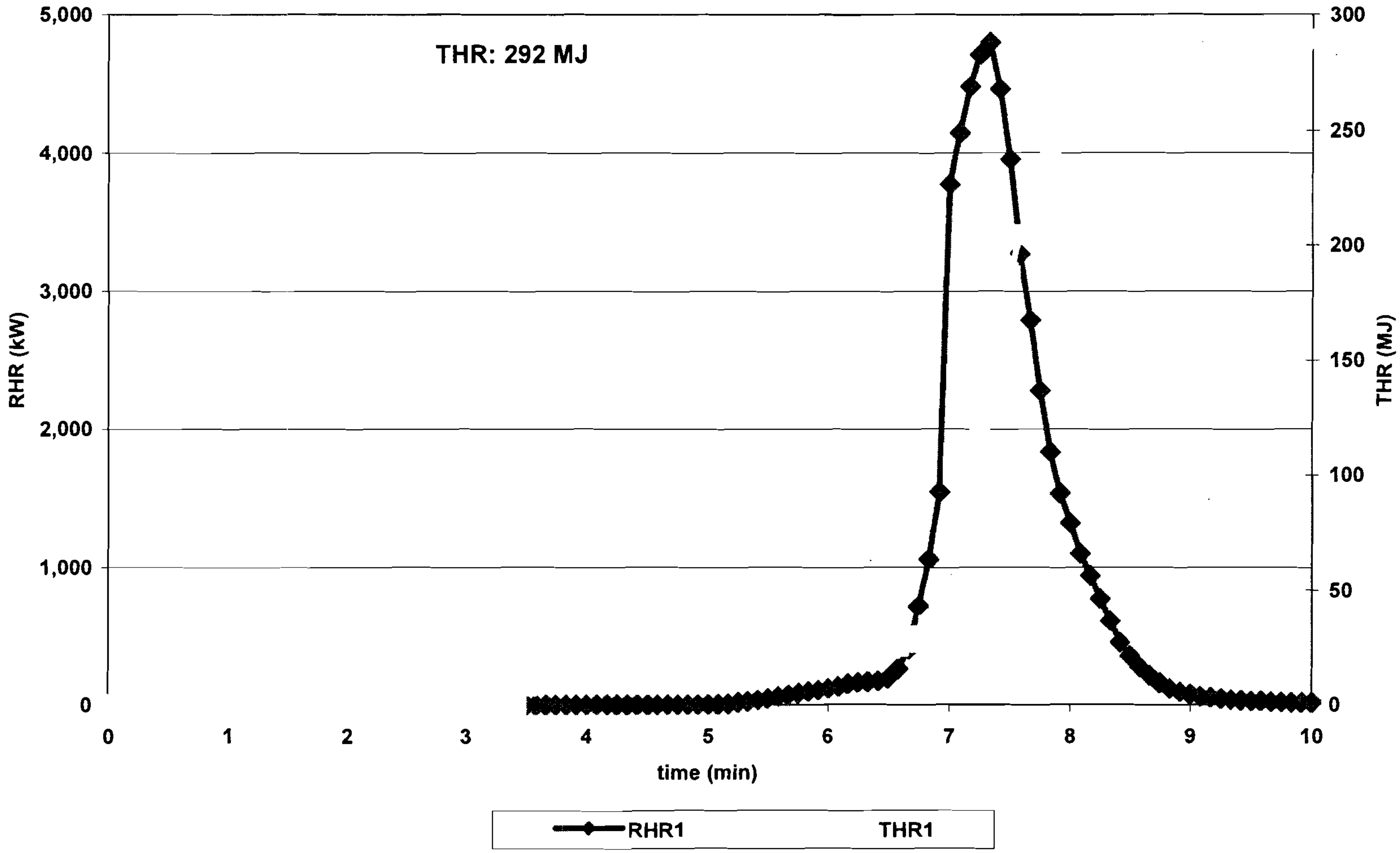


Figure 3: Rate of Heat Release CA TB 117 Foam Sofa 2

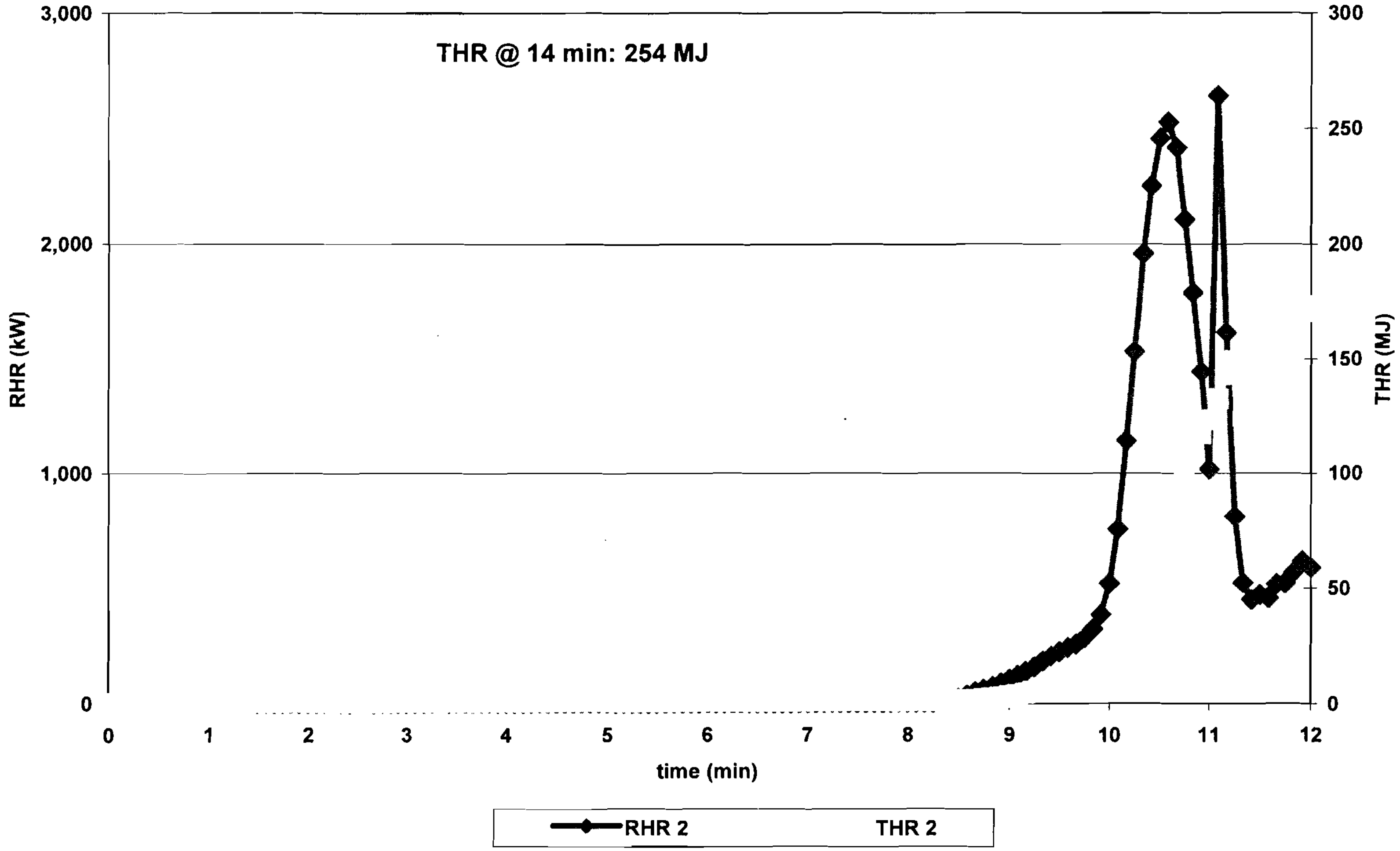


Figure 4: Rate of Heat Release TB 117 Foam Sofa 3

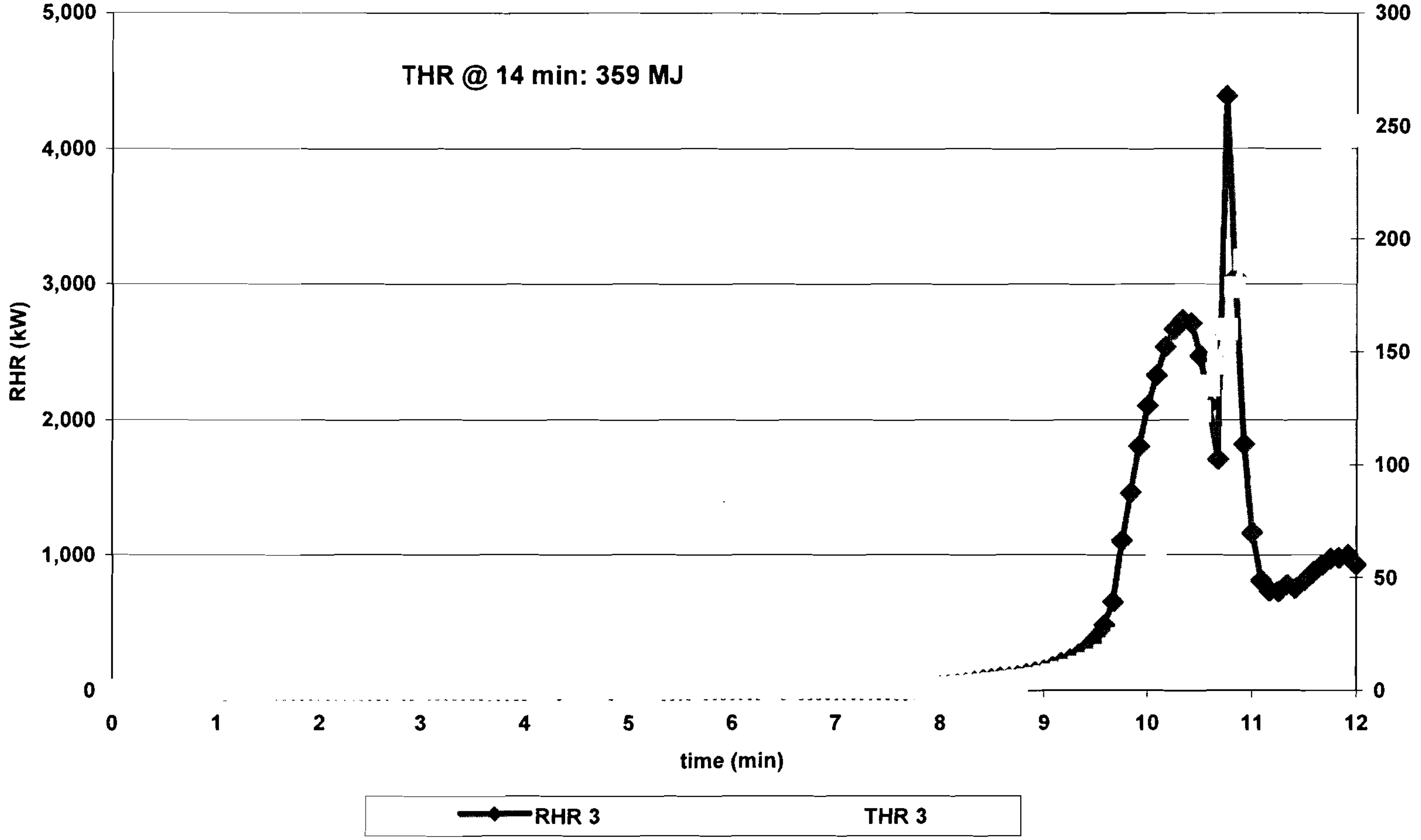


Figure 5: Comparison with Flashover of All US Sofas Tested

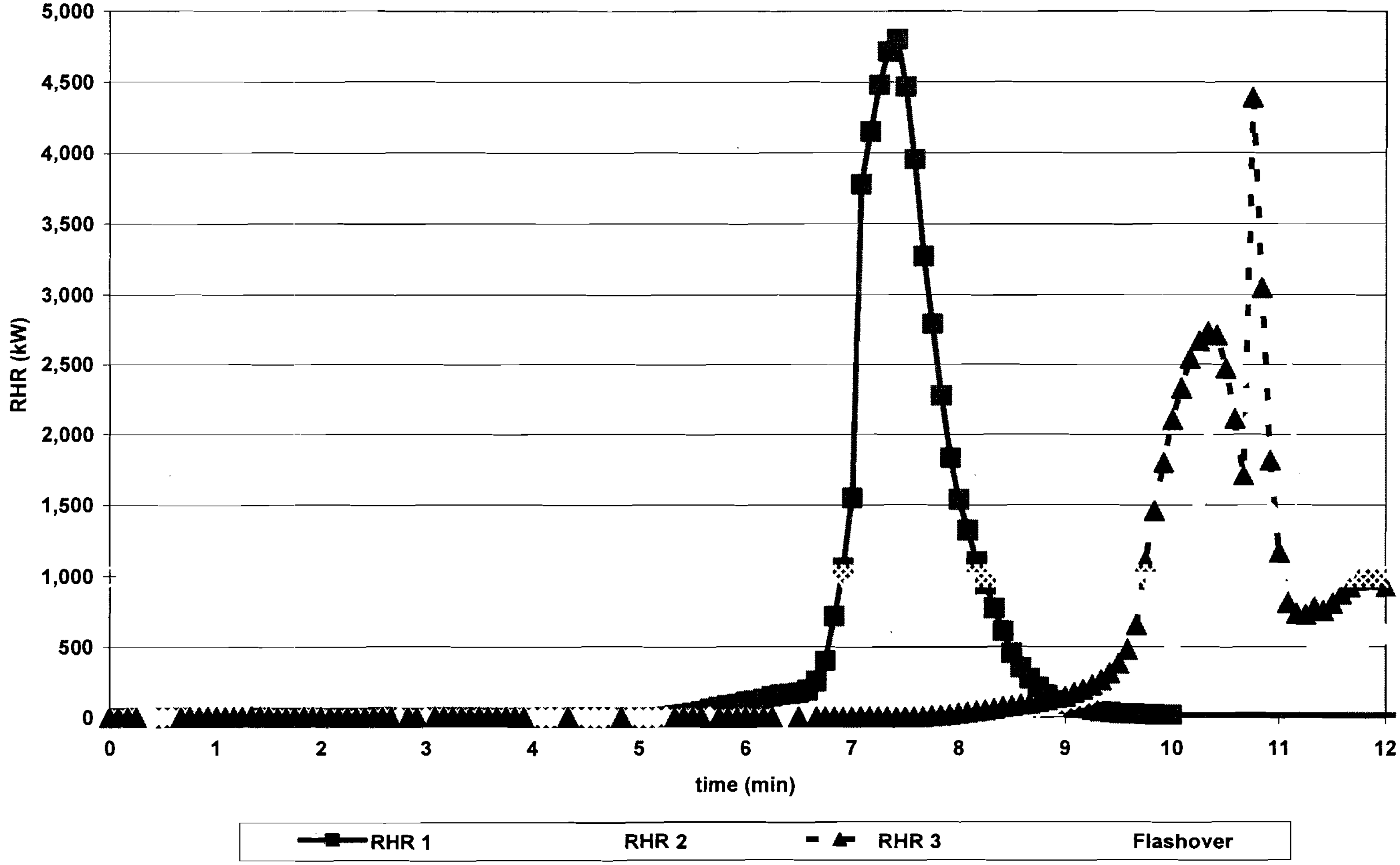


Figure 6: Smoke Release (Rate & Total) All Tests US Sofas

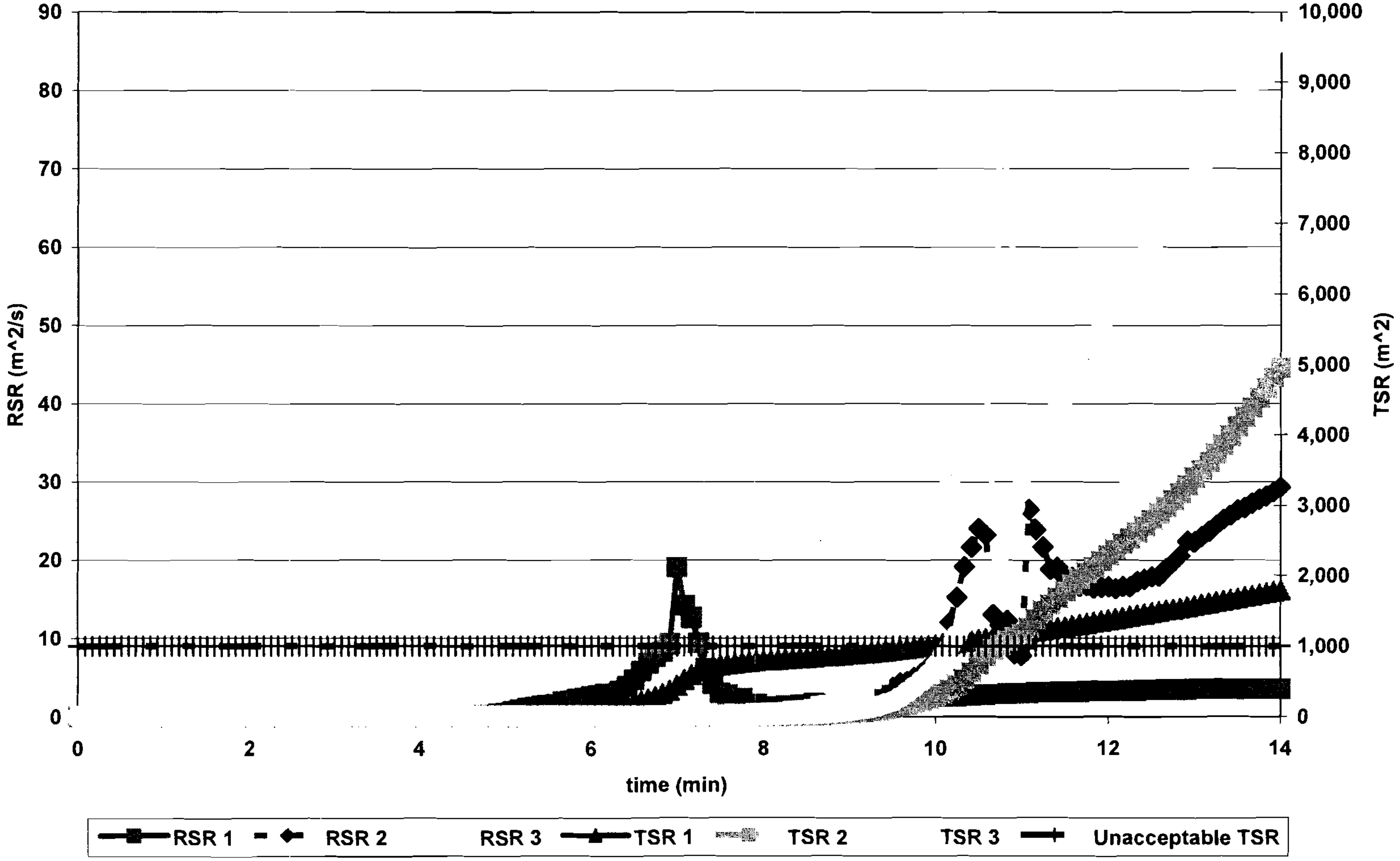
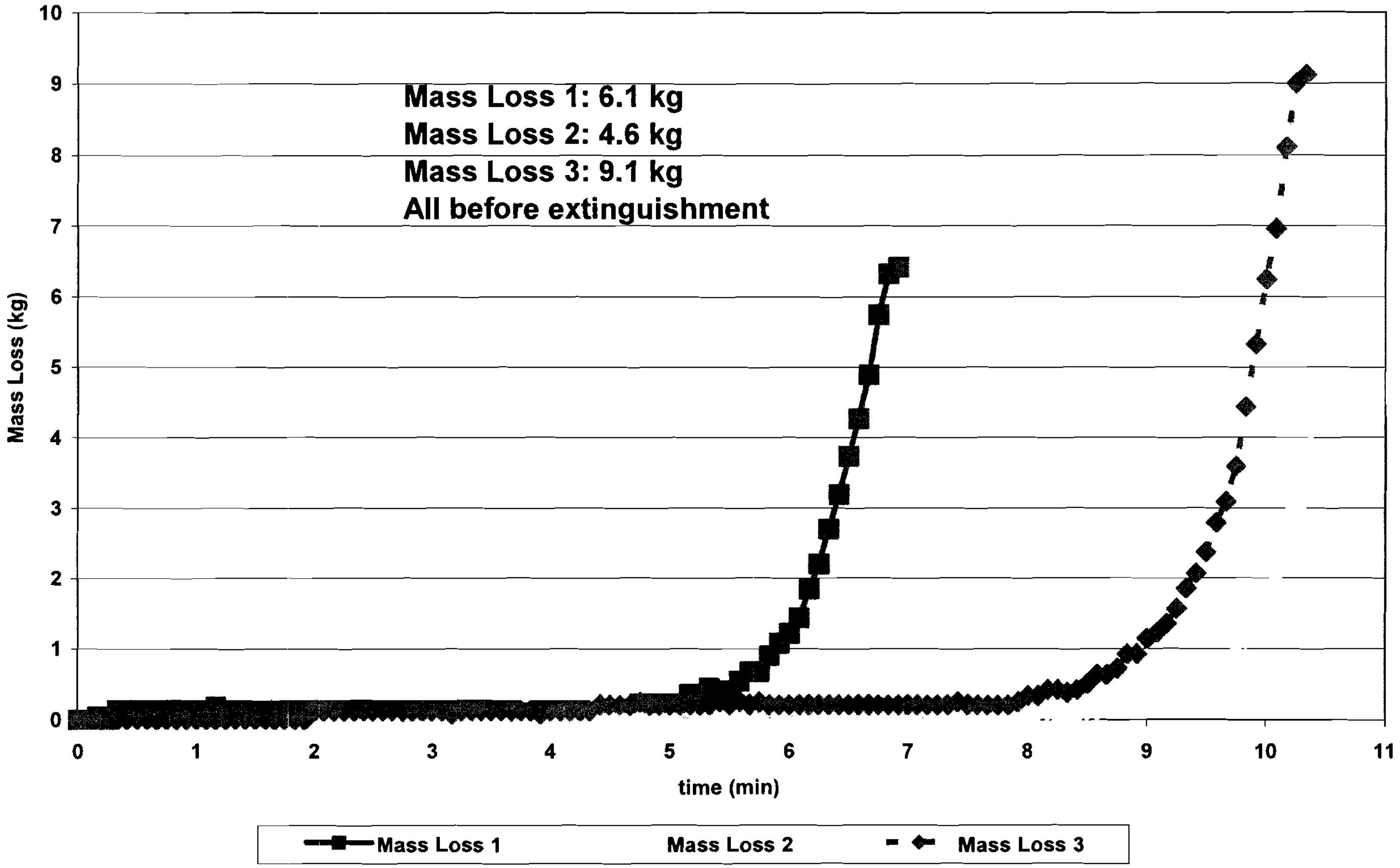


Figure 7: Mass Loss all Tests US Sofas



Mass Loss 1: 6.1 kg
Mass Loss 2: 4.6 kg
Mass Loss 3: 9.1 kg
All before extinguishment

Figure 8: Toxicity Time Line in Test Room From Tests on US Sofas

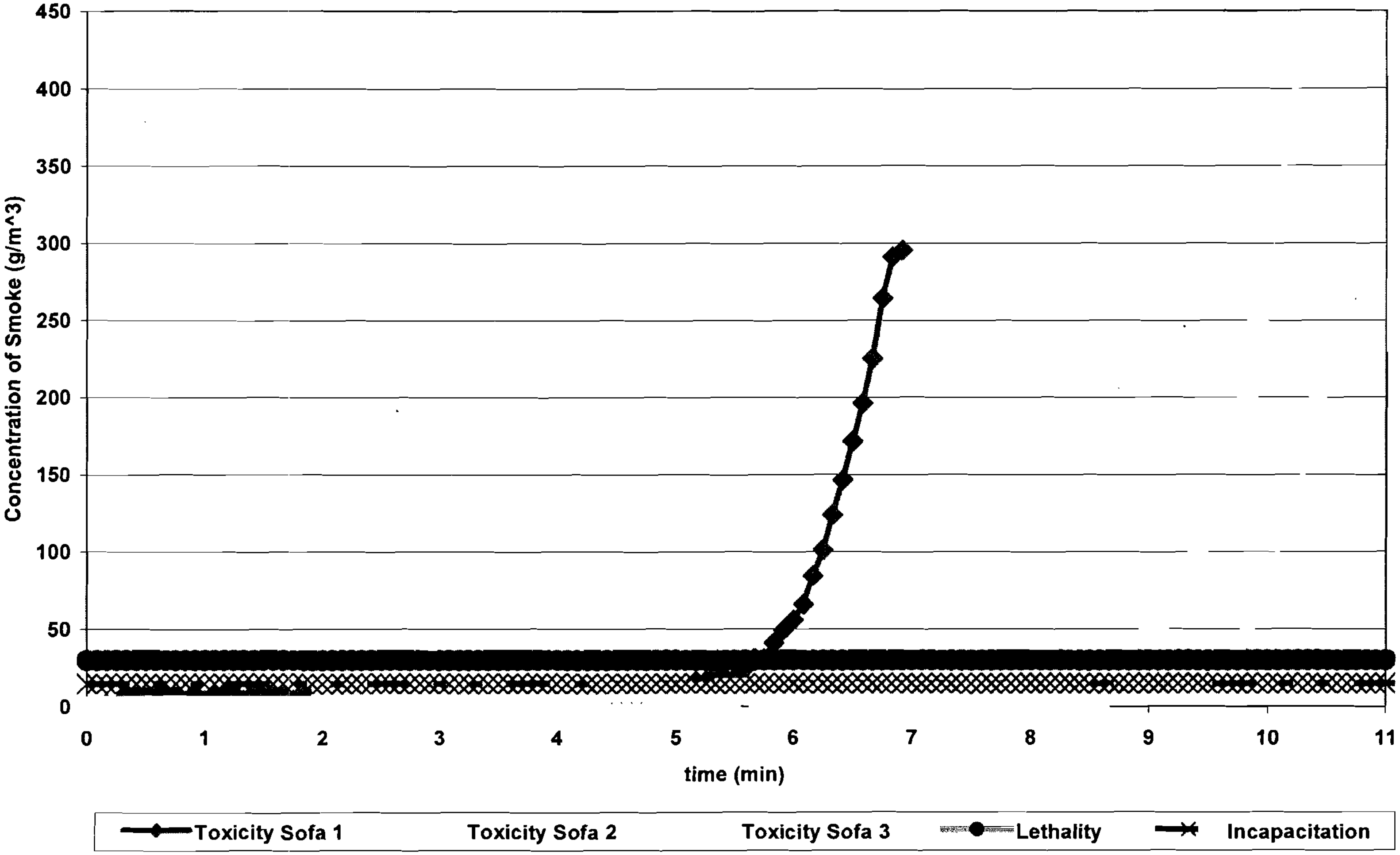
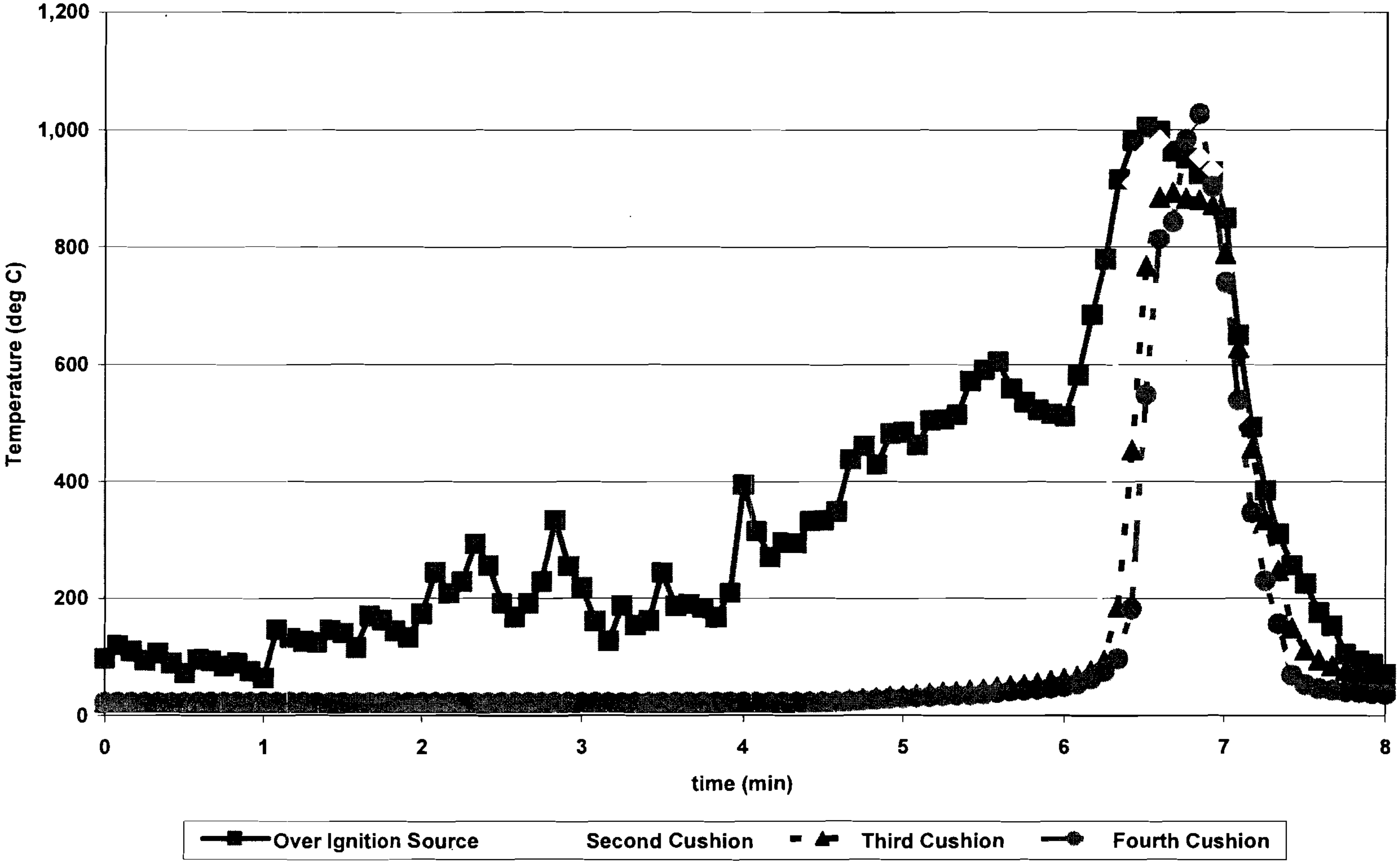


Figure 9: Sofa Temperatures in Test of Sofa With Non CA TB 117 Foam



EXPERIENCES IN FULL SCALE FIRE TESTING OF CONSUMER PRODUCTS

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ABSTRACT

A number of consumer products exhibit very poor fire performance, to a large extent as a result of the lack of regulatory fire safety requirements for such products. Such products include, inter alia, television sets, upholstered furniture, mattresses, personal automobiles and playground structures for children.

The most accurate way to ensure that a consumer product exhibits proper fire performance is to conduct full scale tests in which all the interactions between the various materials and components have the opportunity to become manifest. Furthermore, the most critical property to be measured is the heat release in those tests.

In actual fact, it is likely that full scale fire tests will not form the basis for most fire safety regulation, unless it is clear that the predictive capability of all relevant small scale (or medium scale) tests is insufficient to allow them to be used reliably.

This article will discuss several series of tests conducted, in the United States, on: (a) mattresses (5 series, encompassing a broad range of performance and applications, residential and institutional), (b) residential upholstered furniture (including a product with good fire performance and a product where the paddings were slightly fire retarded), (c) wall coverings (with a wide range of chemical compositions), (d) automobiles (3 vans), (e) a typical plastic garbage can and (f) a children playground structure (which met a performance specification).

The full scale fire tests on mattresses, upholstered furniture, wall coverings and playground structure were conducted indoors, in standard rooms, and heat release (by oxygen consumption calorimetry) as well as smoke release was measured, while also making various other measurements and visual observations. The garbage can test was conducted in the same standard room, but only heat release was measured. The automobile (van) tests were conducted outdoors, and measurements involved exclusively thermocouples and visual observations.

Reference will also be made to work conducted on Christmas trees (both actual full scale tests and computer predictions), on television sets (comparison testing) and predictive work on computer housing fire performance.

The results clearly indicate that some of the consumer products in use in the United States (and in some cases in Europe) are permitted to be unsafe and that improved alternatives exist. Recommendations are presented for all cases. They include, for example, suggested code changes or improved fire test method requirements.

INTRODUCTION

Consumer products are usually not regulated for their fire performance, with a few exceptions. This is probably a mistake in the case of many of them. This work will address a few types of consumer products that can generate large amounts of heat when they ignite and burn. The fire performance of an individual furnishing item is often crucial in determining whether a room becomes untenable in a fire, thus resulting in fire fatalities [1-2]. This study will look at several sets of "large" consumer products and investigate the background, the likelihood of them producing a large fire and potential strategies for improving the fire performance and the safety of the consumers using them.

MATTRESSES AND UPHOLSTERED FURNITURE

Back in the 1970s it was established that upholstered furniture represented a potentially serious concern: a single item can yield a fire severe enough to engulf a whole room and take it to flashover. As a consequence of this, in the USA, the Boston Fire Department and the California Bureau of Home Furnishings (CBHF), independently, developed flaming ignition fire tests for full scale items of upholstered furniture, intended for medium or high risk applications, the most famous being the first edition of California Technical Bulletin 133 (CA TB 133) [3], which had as its principal pass/fail criterion the temperature increase in the test room, which can be correlated with heat release. The test was initially intended to be a "low-tech" tool for qualitative use by manufacturers. In other words, the simple application of the ignition source, with little instrumentation would permit a test user to assess whether the chair would burn vigorously or not. Unfortunately, the output was not usable for more comprehensive assessments of fire safety. CA TB 133 has been used for regulation in several US states, including California (and in codes: NFPA 101 [4], Life Safety Code, NFPA 301 [5], Life Safety Code for Ships, and the International Fire Code, IFC, [6] all require ASTM E 1537 [7], functionally identical), and for specifications since the early 1990s. CBHF soon later also developed a test for mattresses, which is analogous (but not identical) to CA TB 133: CA TB 129 [8] and, more recently, CA TB 603 [9]. However, CA TB 129 was never used for regulations by either the state of California, or any other US state (although it is also included in NFPA 101, NFPA 301 and the IFC, as ASTM E 1590 [10], again functionally identical). CA TB 129/ASTM E 1590 involves exposure of mattresses for 3 min to an 18 kW propane gas flame. CA TB 603, on the other hand, is now a requirement for all mattresses sold in the state of California, and is likely to form the basis for regulation throughout the United States by the Consumer Product Safety Commission.

In the United Kingdom, a different simplistic test was the first serious attempt at developing a flaming ignition standard for upholstered furniture systems: British Standard (BS 5852 [11]). This test uses a variety of wood cribs, and it tests a combination of fabric and filling, made up into two standard cushions: bottom and back. The wood cribs in what was originally part 2 of BS 5852 range from # 4 (weighing 8.5 g), through # 5 (weighing 17 g) to # 7 (weighing 126 g). Less severe ignition sources (originally included in part 1 of BS 5852) address smokers' materials: cigarettes and butane flames simulating matches. An empirical study showed that the "rankings" resulting from testing fabric/foam combinations in this test correlated well with those that could be obtained from using the cone calorimeter at 25 kW/m^2 [12]. The cone calorimeter [13] has been shown to be an effective predictor of whether a product will cause flashover on its own [2], and it is particularly effective when used for upholstery composites with the ASTM E1474 protocol [14]. Following its initial adoption, BS 5852 has been modified somewhat, so that testing for qualification is now done effectively on separate items. Fillings are qualified when tested under a "standard" flame retarded polyester fabric and fabrics are qualified when tested over a filling deemed acceptable. Thus, it is not required to test the system actually proposed for use, which makes testing more accessible to materials manufacturers (and less costly for them), as they need not test the large variety of potential finished systems. The British government issued the Furniture and Furnishings Fire Regulations Act in 1988, which requires all fabric and polyurethane foams used in the construction of upholstered furniture to meet BS 5852, crib #5 fire test requirements, and all filling materials in mattresses, including cot mattresses, to meet the same regulations. In other words, no filling or padding materials sold for use in upholstered furniture or in mattresses in the United Kingdom is permitted to ignite and spread flame when exposed to a crib # 5, while covered by a standard fire retarded polyester fabric (the fabric does not actually protect from ignition).

Requirements to protect the public from smoldering fires have been in effect both in the USA and in the UK for a large number of years. In the USA, residential upholstered furniture components generally meet a voluntary smoldering ignition standard nationwide, as administered by the Upholstered Furniture Action Council, since the late 1970s, with mandatory requirements in place in California (where small flame ignition requirements also exist, although upholstered furniture that does not meet any open flame requirements can be sold in California, as long as it is labeled as not meeting the requirements) and in some other jurisdictions. All mattress and mattress pads (including residential) are required, since 1972, to comply with 16 CFR Part 1632 [15]: a smoldering ignition (by cigarettes) test method. This test method has been instrumental in heavily decreasing (and virtually eliminating) cases where a mattress undergoes flaming combustion resulting from ignition by a smoldering cigarette, usually by replacing cellulosic padding or filling materials (such as cotton) with non smoldering plastic materials. However, there are no requirements for flaming ignition of mattresses or mattress pads, or of their components, in the USA, other than requirements for ASTM E 1590 in some high risk applications in codes.

In the UK, the Department of Trade and Industry commissioned a study to look at the effects of the 1988 legislation in terms of lives saved, decreased number of injuries and economic impact [16] (based on the exchange rate, in 1992, of £1=$1.5). Some of the key improvements are shown in Table 1, based on an official UK government publication, for upholstered furniture only. The study indicates that 710 lives (and over £5 billion) were saved over a 10 year period, in spite of the relatively low smoke detector penetration into the UK. In fact, a follow-up UK study shows that neither smoke detector penetration nor the changes in smoking patterns can explain the improvement in fire losses [17]. Significant savings should also be expected from mattress and bedding fires. In both cases, the number of fire fatalities has been decreasing, and much more than in the US. A particularly important aspect of the UK study has been the economic analysis, included the cost to industry (which, by and large, was not passed on to the consumer) of developing and selling products with greatly improved fire performance.

This study presents results of 5 series of full scale fire tests of mattresses, and one series of full scale fire tests of upholstered furniture, involving the following products:

- Six US mattresses intended for institutional (detention) application
- US modern adult residential, US old adult residential and UK adult residential
- US baby residential and UK baby residential (without and with sheet)
- Two US adult mattresses suitable for residential use
- US adult residential and UK adult residential (without and with sheet)
- Four sofas (3 US modern residential and one UK modern residential).

Table 1 - Benefits Resulting From UK Upholstery Regulations			
Benefit measure	Annual benefit 1992	Annual benefit 1997	Cumulative benefit 1988-1997
Number of dwelling fires	3,715	8,769	42,754
Total lives saved	169	362	1,856
Lives saved for upholstery as item first ignited	65	138	7,100
Total non-fatal injuries saved	1,548	3,315	17,000
Injuries saved for upholstery as item first ignited	526	1,126	5,774
Loss adjusted cost saving £m/yr	23	53	249
Final cost saving £m/yr	507	10,835	5,567
Total cost saving £m/yr	530	1,138	5,615

All six series of tests were conducted in a standard "ASTM" or "ISO" room. The room dimensions are: 2.4 m x 3.7 m x 2.4 m, with a door of 0.76 m, centered on one of the short walls, and with an exhaust duct just outside the room. Measurements were the type of measurements recommended for all large-scale heat release tests: heat release (by oxygen consumption calorimetry), smoke release in the duct and temperature measurements at various locations in the room and duct. Mass loss and heat fluxes were also measured in some cases.

Series 1 [18]: The fire tests involved six solid core mattresses (size: 1.9 m x 0.8 m x 76 mm thick), containing exclusively commercial materials, and designed for detention occupancies, all covered by a fluid resistant vinyl cover, 360 g/m^2. The mattress paddings are shown below:

(a) Cotton batting, fire retarded (FR Cotton)
(b) Combustion modified high resilient polyurethane cushioning A (FR PU A)
(c) Combustion modified high resilient polyurethane cushioning B (FR PU B)
(d) Densified polyester batting, fire retarded (FR Polyester)
(e) Polychloroprene compound cushioning, fire retarded (Neoprene)
(f) Commercial highly fire retarded foam (FR PU C)

All the mattresses had been shown to comply with the criteria of ASTM E 1590 as shown in NFPA 101 (namely 250 kW peak rate of heat release and 40 MJ maximum heat released after 10 min). They were tested in 1996 using a 50 kW exposure detention mattress test (designed specifically for detention mattresses [19], which is specifically recommended for such products in ASTM F 1870 [20]), and the main results are shown in Table 2. The test exposes mattresses from the top, with the burner simulating the heat release of a detention clothing ignition source (1 sweatshirt [50% cotton/50% polyester blend], 1 T-shirt [50% cotton/50% polyester blend], 1 pair of blue denim trousers [100% cotton] and 12 double sheets of newspaper: rough weight 1 kg).

Series 2 [21]: Three commercial residential inner spring mattresses were obtained, all with a textile ticking: (a) a queen-size mattress, intended for residential use, purchased commercially in California (USA) in the 1990s; (b) a mattress made by the same manufacturer (in the USA) and built in 1937, constructed mostly with cotton materials (before the requirements for mattresses not to ignite from cigarette smoldering), and (c) a UK residential mattress purchased commercially in the UK in the year 1999. The modern US mattress was a typical mattress used throughout the country, and its cost was average for such mattresses; the UK mattress was a chosen as one of the most inexpensive mattresses available. The tests were conducted in the year 2000. The "old" mattress (made in 1937) failed the smoldering ignition test, so that a cigarette would have eventually caused it to catch on fire. However, when ignited by a simulated match (BS 5852 Ignition Source 1; flame applied for 20 s), its peak rate of heat release was only 114 kW, with maximum temperatures of ca. 180°C in the room (and that fire took well over an hour to get going). The new US mattress caused flashover on its own and released heat at a rate of well over 1.5 MW (with temperatures up to 920°C), when ignited simply by the simulated match. The fire had to be extinguished at that heat release level to prevent damage to the facility. The UK residential mattress was exposed to both the simulated match and to a 17 g wood crib (BS 5852, Ignition Source # 5): it did not release any significant amount of heat in either case. The major test results are shown in Table 3.

Series 3 [21]: Two commercial residential solid core baby mattresses (intended for use in baby cribs) were obtained: one purchased commercially in Texas (USA) in the 1990s; and one purchased commercially in the UK in the year 2000. The US baby mattress was constructed of solid core non fire retarded polyurethane foam (its size was, of course, only a fraction of the size of the modern residential queen-size mattress tested in Series 2, and weighed some 20 times less). Both mattresses were chosen among the most inexpensive mattresses available in the range. The tests were conducted in the year 2000. The US baby mattress ignited easily (although the vinyl cover resisted the simulated match ignition), released over 250 kW and gave a peak temperature of 226°C in the same standard room. Both mattresses were also tested with a baby sheet (50/50 polyester/cotton) and a cotton comforter; the ignition source used for these tests was the simulated match (BS 5852 Ignition Source # 1). The US baby mattress ignited easily again and gave off high levels of heat and smoke. On the other the UK mattress released no significant amount of heat, when tested both with and without sheet and comforter, but it did release some smoke when the sheet and comforter were used. The major results of the tests are shown in Table 4.

Series 4 [22]: Two adult commercial mattresses were purchased commercially in the year 2001 in the United States. One of the mattresses (labeled FR Mattress) was a solid core foam mattress, with ticking, designed with fire retarded technology commercially available in the early 1990's; it had a medium-to-low price. Its size was approximately 1.5 m x 2.0 m x 0.18 m. The other mattress (labeled Non FR Mattress) was an air mattress, with foam surround pieces, manufactured between 1995 and 1997, at the luxury end of the mattress price scale. It was probably not fire retarded. Its size was approximately 1.9 m x 2.0 m x 0.20 m. The mattress was hooked up to pump and inflated prior to testing. Both tests used identical sheets: a top and a bottom sheet, both 50/50 polyester/cotton. The tests were conducted in the year 2001. In these tests, three thermocouples were placed inside the room: TC1 (center of room, 0.1 m below ceiling), TC2 (at foot of bed, on top of the sheets, i.e. by ignition source) and TC3 (center of doorway, 0.1 m below doorway top). The ignition source was a small cigarette lighter, applied at the middle of the foot of the bed, at a height corresponding to the base of the mattress. The major results of the tests are shown in Table 5. While the FR mattress caused a minimal fire, the Non FR mattress caused flashover in the room, which had to be extinguished manually.

Series 5 [23]: Four commercial adult residential inner-spring mattresses were purchased in the year 2001: 2 identical ones in the USA and 2 identical ones in the UK, all of them among the more inexpensive mattresses available. One pair of the mattresses was tested without sheets and the other pair with a single fitted 50/50 polyester/cotton sheet. The US mattress, both without and with a sheet, ignited with a simulated match (@ 8 s) and lost 90% of its mass within < 8 min (a bit slower with the sheet). The UK mattress, when tested without the sheet, did not ignite with a simulated match, and did not fully ignite either with a BS 5852 crib 4 or a BS 5852 crib 5 ignition source (peak heat release rate in the test: 5 kW, minimal mass loss). The UK mattress, when tested with the sheet, also did not ignite with the simulated match, but the sheet ignited after 1 min 40 s with a BS 5852 crib 5 ignition source, with the mattress ticking then igniting at 12 min 27 s after the start of the test. For the next 37 min, a very small fire continued, until 50 kW was reached at 49 min 50 s after the start of the test, with peak rate of heat release and 90% mass loss at 53-56 min after the start of the test.

Series 6 [24]***:*** Three sofas were manufactured in the US and were sectional sofas; two of them contained foam mildly fire retarded to CA TB 117 [25] and one did not (US Sofa 1). The other sofa was a standard residential sofa purchased in the UK. The ignition sources used for all tests were based on BS 5852. BS 5852 Ignition source 1 was used on all sofas, and the ignition was conducted in the seat section of one cushion (a section less prone to ignition than the side arm, the back or any edges). The ignition source is a butane gas flame with a 45 mL/min flow rate and a total application time of 20 s, simulating a match. Only US Sofa 1 ignited with this ignition source, and quickly developed a self-propagating fire. The other three sofas were then subjected to BS 5852 Ignition source 2, which is a butane gas flame with a 160 mL/min flow rate and a total application time of 40 s. Both the other US sofas ignited with this ignition source, and quickly developed a self-propagating fire. The UK sofa did not ignite with either ignition source. Table 6 contains the summary information of the principal data of all large scale tests. Three of the 4 tests had to be extinguished soon after flashover to prevent damaging the test facility. At the time of extinguishment none of them had reached their maximum rate of heat release and the values of peak rate of heat release reported in Table 6 are those just before extinguishment. Similarly, the total smoke released is reported at 540 s, shortly after extinguishment for the US sofas, at the same time for all tests. It is noteworthy that the time until a self-propagating fire was obtained differed only by about 1 minute among the three US sofas, with the sofas containing foam complying with CA TB 117 taking just somewhat longer time to become a fire that went out of control. The sofa purchased in the UK did not ignite (with either ignition source) and the small flame (on the surface) gave a maximum rate of heat release of ca. 2 kW, and virtually unmeasurable amounts of smoke and mass loss.

Table 2. Test Results Obtained for Detention (Series 1) Mattresses With 50 kW Mattress Test

	Pk RHR	Time Pk	THR	Pk Room Temp	Time to Pk Temp	Wt Loss	Peak [CO]
	kW	S	MJ	°C	s	%	ppm
FR Cotton	89.3	96	18.80	152	36	1.6	381
FR PU A	138.5	114	42.90	175	156	10.9	234
FR PU B	119.6	102	27.90	160	72	6.2	981
FR Polyester	421.6	312	89.60	303	300	67.5	1818
Neoprene	76.7	246	19.40	138	72	2.4	72
FR PU C	81.6	186	19.90	125	222	0.7	87
	Pk Room Smoke	Time to Pk Smoke	Pk RSR	Time to Pk RSR	TSR	Time to 50 kW	CO Yield
	%	S	m^2/s	s	m^2	s	ppm min
FR Cotton	9.6	96	1.5	42	98.1	36	637
FR PU A	96.1	462	1.5	48	327.8	36	96
FR PU B	99.1	60	2.1	96	384.2	54	2171
FR Polyester	100	2.9	13.1	324	2251.6	48	4387
Neoprene	59.5	78	0.7	78	60.9	54	45
FR PU C	84.3	60	0.8	66	67.2	54	50

Table 3. Major Results of Series 2 Mattress Tests			
	US Adult Residential Mattress Pre Requirement	UK Adult Residential Mattress (1990s)	US Adult Residential Mattress (1990s)
Peak RHR (kW)	113.9	1.3	1655 (water)
THR (MJ)	127.4	0.1	110.4
Avg RHR (kW)	25.4 (19.5)	0.2	128.8
THR 10 min (MJ)	0.3 (0.0)	0.1	86.7
Peak RSR (m^2/s)	1.14	0.0	18.10
TSR (m^2)	528	0.0	1074
Avg RSR (m^2/s)	0.11 (0.08)	0.0	0.74
TSR @ 10 min (m^2)	0.9 (0.0)	0.0	18.1
Peak OD	0.41	0.0	2.74
Avg OD	0.04 (0.03)	0.0	0.13
Flashover Time (s)	NA	NA	564
Time Peak RHR (s)	3048 (4578)	150	582 (water)
Mass Loss (%)	72.8	0.3	18.0
Peak Heat Flux (kW/m^2)	NM	NM	NM
Ignition source	Cigarette - BS 5852 # 1	BS 5852 # 5	BS 5852 # 1

Note 1: US Adult Residential Mattress Pre Requirement: values calculated from application of match; values in parentheses calculated from application of cigarette. Flaming ignition resulted from first match application.

Note 2: US Adult Residential Mattress (CA 1995): Values for peak rate of heat release and total heat release must be adjusted as the fire was extinguished within a few seconds of it reaching flashover, when less than 20% of the mattress had been burnt.

Note 3: NA: as flashover did not occur, flashover time is not applicable; NM: not measured.

Note 4: Both cigarette and simulated match were used. Match caused the propagation.

Table 4. Major Results of Series 3 Mattress Tests			
	US Baby Residential Mattress	UK Baby Residential Mattress	UK Baby Mattress + Bedding
Peak RHR (kW)	255	2	10
THR (MJ)	29.6	0.4	2.3
Avg RHR (kW)	45.8	0.9	3.7
THR 10 min (MJ)	29.0	0.4	2.3
Peak RSR (m^2/s)	7.51	0.004	0.14
TSR (m^2)	815	0.22	22
Avg RSR (m^2/s)	1.26	0.00	0.04
TSR @ 10 min (m^2)	813	0.22	22
Peak OD	1.48	0.002	0.05
Avg OD	0.26	0.00	0.01
Flashover Time (s)	NA	NA	NA
Time Peak RHR (s)	405	165	270
Mass Loss (%)	91.8	0.0	14.6
Peak Heat Flux (kW/m^2)	2.1	0.0	0.1
Ignition source	BS 5852 # 5	BS 5852 # 5	BS 5852 # 1

Table 5. Major Results of Series 4 Mattress Tests		
Property	**Non FR Mattress**	**FR Mattress**
Peak RHR (kW)	3,553	42
Smoke Obscuration (%)	98.0	21.5
Peak CO (ppm)	11,185	347
Time to Flashover (s)	264	Did not occur
Time to Extinguishment (s)	420	Not needed
Peak Temperature TC1 (°C)	516	20
Peak Temperature TC2 (°C)	305	312
Peak Temperature TC3 (°C)	557	16

Table 6. Major Data from all 4 Large Scale Furniture Tests

	US Sofa 1	US Sofa 2	US Sofa 3	UK Sofa
Ignition Source	BS 5852 1	BS 5852 2	BS 5852 2	BS 5852 2
Extinguishment@ (s)	485	480	486	No ignition
Pk RHR (kW) (before extinguishment)	4,802	2,641	4,394	2
Time to flashover (s)	410	465	447	No ignition
Time to Pk RHR (s)	440	498	485	No ignition
Time before self-propagating fire (s)	310	378	372	No ignition
Total Heat Release @ 600 s (MJ)	292	251	359	No ignition
Flashover RHR in Test Room (kW)	1,000	1,000	1,000	1,000
Total Smoke Release @ 540 s (in m^2)	889	2,535	6,389	No ignition
Maximum Smoke Release (Code, in m^2)	1,000	1,000	1,000	1,000
Mass of Sofa (kg)	290	276	275	56
Mass Loss Before Extinguishment (kg)	6.1	4.6	9.1	No ignition
Maximum Toxic Smoke Concentration in Test Room Before Extinguishment (g/m^3) *	295	212	420	No ignition
Toxic Smoke Incapacitation Limit (g/m^3)	15	15	15	15
Time to Toxic Smoke Incapacitation Concentration in Test Room (s)	310	420	384	No ignition
Toxic Smoke Lethality Limit (g/m^3) *	30	30	30	30
Time to Toxic Smoke Lethality Concentration in Test Room (s)	340	441	411	No ignition

Note: * Based on smoke concentration for a 30 minute exposure period or the equivalent concentration-time product. This is calculated from the mass lost and the room volume and not from the measurements of toxic gases themselves, and includes all toxic species.

The series 2 mattress test data show how, while a typical US adult residential mattresses exhibits rapid ignition leading to flashover conditions with a small ignition source (a match), an inexpensive commercial alternative exists in the UK, which would not ignite under similar conditions. Both modern adult mattresses had polyurethane foam as filling material (however, whereas the one from the UK was fire retarded, the one from the US was not; also the modern US mattress had multiple layers in the filling, with the non FR polyurethane foam being the largest layer), while the old mattress had a cotton ticking and cotton filling. Thus, while the old mattress was able to be ignited by a smoldering cigarette, in a fire that smoldered very slowly but progressively, fast flaming ignition actually resulted only from the action of the simulated match. Smoke release in the room followed the pattern expected from the heat release data: if the mattresses released abundant heat, they also caused abundant smoke obscuration [26]. The series 4 mattress test data shows the exact same pattern as series 2 mattress tests, but for a comparison between a luxury US adult residential mattress and an inexpensive US alternative. The US FR mattress is most often used for institutional applications but is available for residential use. The difference in fire performance is, of course, considerable. For example, a European project (CBUF) investigating fire performance of upholstered furniture and mattresses does not even consider that "real ignition" has occurred until a product has released 50 kW [27]. Thus, while the FR mattress barely ignited (42 kW peak rate of heat release, including the sheet), the non FR mattress caused flashover in the room before the fire was manually extinguished. The series 3 mattress test data shows that US mattresses made for the infant market are equally poor in fire performance to those made for their parents. Thus, while flashover cannot be reached from a fire involving one baby mattress alone, due to its small size, differences in fire performance between the US and UK mattresses are as pronounced as those for adults. The series 1 mattress test data shows that the peak rate of heat release for five of the detention mattresses did not exceed 150 kW (and for 3 of them did not exceed 100 kW), while one mattress performed rather poorly, while losing about 60% of its mass in roughly 8 min. However, the severity of the ignition source must be taken into account: 50 kW for 5 min. Even the poorest performer would have released much less heat if exposed to the ASTM E 1590 ignition source: even the FR polyester mattress would have release < 250 kW. Clearly, the technology exists for making institutional mattresses with excellent fire performance, and that can resist extremely severe ignition sources. Even more importantly, the technology for achieving good mattress fire performance does not rely on a single type of material: modified polyurethane foams, polychloroprene foams and fire retarded cotton fillings can all be used to obtain excellent mattress fire performance. The series 5 mattress test data also shows that the UK legislation has led to significant improvements in mattress fire safety, since: (a) the US mattress tested ignited very rapidly (within 8 s) from a simulated match source, (b) the US mattress tested was 90% consumed within < 8 min from a simulated match source, (c) the UK mattress tested did not ignite from either a simulated match or a # 5 wood crib ignition source, (d) the US mattress tested ignited very rapidly (within 12 s) from a simulated match source, when covered by a sheet, (e) the US mattress tested was 90% consumed within < 12 min from a simulated match source, when covered by a sheet, (f) the UK mattress tested did not ignite from a simulated match ignition source, even when covered by a sheet, (g) the UK mattress tested did not ignite until > 12 min from a # 5 wood crib ignition source, when covered by a sheet and (h) the UK mattress tested took almost an hour to be 90% consumed after ignition from a # 5 wood crib ignition, when covered by a sheet. However, series 5 test data also shows that further protection of the entire UK mattress from severe ignition sources would still be desirable. The legislation in the UK on mattresses has been aimed primarily at ignition, and additional requirements based on fire performance (or perhaps heat release) of the entire mattress would result in even greater fire safety. Tests conducted using the cone calorimeter applications standard for upholstered fabric and mattress composites, ASTM E1474 [14] for mattresses in series 2 and 3 make it clear that the principal source of heat release is the filling, since the peak heat release rates of the two modern US mattresses (adult new series 2 and baby series 3) are virtually the same, in spite of the different cover materials. Of course, the total heat released by both mattresses was very different, and reflected the significant difference in mass. The peak and average rates of heat release in the cone tests of the new adult US residential mattress (series 2) were sufficiently high to clearly indicate that flashover was likely to occur [2], as it indeed did in the room test. The values for the US baby mattress (series 3) were borderline, with a very high peak and a smaller average (again due to the small mass), which is consistent with having had a high rate of heat release in the room test, but insufficient for flashover. Data analysis indicates that the other samples (UK mattresses series 2 and 3, or old US mattress series 2) were unlikely to cause flashover, as was indeed the case. Smoke release was significant for all samples, except for the old US mattress (series 2), indicating that smoke is more difficult to predict than heat release, confirming an earlier finding that the cover has a much larger effect in cone calorimeter tests than it has in full-scale tests. The poor fire performance of US residential mattresses has been well known for a number of years [28], particularly following a critical study conducted in 1991, at the California Bureau of Home Furnishings and Thermal Insulation (CBHF), on mattresses and bedding systems [29]. The study found that single mattresses could lead to rates of heat release of almost 2 MW (with room temperatures exceeding 1,000°C) in a small room (with the tests ending in manual extinguishment, to prevent fire damage to the facility). Mattresses similar to those that resulted in the high intensity CBHF fire tests can still be purchased commercially throughout the USA: solid core non fire retarded conventional polyurethane foam, 150 mm (6 in) thick, at 24 kg/m^3 density, with quilting and ticking. The

CBHF study also showed that viable mattresses were available that released no more than 20-30 kW and caused room temperatures of < 100°C. Furthermore, CBHF had also conducted earlier studies (on detention facility mattresses) indicating that mattresses could be manufactured that caused very low temperature increases in the same room (maximum temperatures < 100°C), one of them being a cotton mattress [xx]. In spite of this information, which has now been available for over 20 years, residential mattresses are being sold in the USA with very poor fire performance; such mattresses endanger the lives of the people using them.

The upholstered furniture tests also led to similar conclusions: (a) residential upholstered furniture in the US often has very poor fire performance, (b) corresponding residential upholstered furniture in the UK has adequate fire performance, including excellent ignition performance, (c) the technology exists in the US (just like in the UK) to make upholstered furniture with excellent fire performance, (d) fire safety regulations addressing open flame ignition, exists in the UK, (e) fire safety of contract upholstered furniture in the US is governed by codes and specifications, but only for some institutional environments and (f) the use of appropriately fire-safe upholstered furniture in the US would result in considerable decreases in fire losses and probably economic savings (since that has occurred in the UK).

WALL COVERINGS (INTERIOR FINISH)

Ten construction materials were tested in a room-corner test configuration [30], using the NFPA 265 (40/150 kW ignition source test [31]), to study heat release and smoke obscuration. The materials were chosen to illustrate adequate fire performance, in terms of heat release and flame spread, together with a broad range of smoke release performances. The same materials were also tested using the ASTM E84 (Steiner tunnel,[32]) test. Only a single one of the materials chosen caused flashover in the room (with an ASTM E84 flame spread index exceeding 25). Similarly, only a single material failed to meet an ASTM E84 smoke development index of 450 (even though that material had a very low ASTM E84 flame spread index and very low heat release rate), and had very high room smoke release. The results indicated that: (a) limits for smoke release need to be set in the room-corner test and (b) that most materials performing well in the room-corner test release low smoke. Similar results were also obtained in a number of other studies, showing that, on average, about one tenth of the materials with low heat release can generate high smoke release.

The materials tested are described in Table 7. Six materials are typically used for wall interior finish: two vinyl wall coverings, a textile wall covering, a thermoplastic sheet, a varnished wood product, and a composite panel. One material is intended for use as ceiling interior finish (ceiling tile). Three materials are normally used as insulation: polyimide foam, phenolic foam and mineral wool.

The NFPA 265 room-corner tests were conducted in a standard "ASTM" or "ISO" room, similar to that for the mattress and upholstered furniture tests. The method uses a propane gas burner to produce a diffusion flame to expose the walls in the corner of the room with a rate of heat output of 40 kW for 5 min followed by 150 kW for 10 min, for a total exposure period of 15 min. The propane gas burner is located such that the edge of the diffusion surface is 51 mm from both walls, in a corner of the room, opposite the door. A total heat flux gauge (calorimeter) is mounted 26 mm above the floor, facing upward, in the geometric center of the test room. An initial volumetric flow rate of 0.94 m^3/s is established through the duct. Within 10 s following the 5 minutes 40 kW exposure, the gas flow is increased to a burner heat release rate of 150 kW, for 10 min. The ignition burner is shut off 15 min after start of the test and the test terminated.

Table 7. Materials Tested per NFPA 265 and ASTM E84

Material	Thickness (mm)	Density (kg/m^3)	Other Information
Ceiling Tile	15	500	Ceramic panel
FR Composite Panel	11	860	Multiple layers*
Mineral Wool	51	115	Unfaced
Phenolic Foam	38	35	Unfaced
Pine	10	32	Varnished plank
Polyimide Foam	51	6.4	Unfaced
Textile Vinyl Wall Covering, on Calcium Silicate Board	11	875	Surface layer: 400 g/m^2
Thermoplastic Sheet	3	1,180	Unfaced
Expanded Vinyl Wallcovering, on Gypsum Board	13	750	Surface layer: 850 g/m^2
Commercial Vinyl Wallcovering, on Gypsum Board	13	720	Surface layer: 480 g/m^2

* Top layer (face) is a high pressure decorative laminate, 0.76 mm thick, adhered with a resorcinol adhesive to a 10 mm FR particle board, adhered with the same adhesive to the back face, a high pressure laminate, 0.66 mm thick.

In the ASTM E84 test method a methane gas burner is set at a gas flow rate adequate to provide a flame extending 1.37 m, exposing the underside of construction materials for 10 min. This corresponds to flow rate of ca. 79 kW (300,000 BTU/hr). The fire test chamber consists of a horizontal duct, 7.6 m long and 448 mm wide. Its sides and base are lined with insulating masonry, and one is provided with a row of high temperature glass pressure-tight observation windows, located so that the entire length of the specimens being tested is observable from outside the fire test chamber. A removable noncombustible insulated top cover seals the chamber. Smoke obscuration is measured with a 12-V sealed beam, clear lens, auto spot lamp, operated from a dc light source, and mounted downstream of the chamber on a horizontal section of the exhaust duct at a point at which there is fully mixed flow. The light beam is directed upward along the vertical axis of the vent pipe. The vent pipe is insulated with high temperature mineral insulation from the vent end of the chamber to the photometer location. A photoelectric cell having an output directly proportional to the amount of light received is mounted over the light source with an overall light-to-cell path distance of 910 mm, 406 mm of which is taken up by the smoke in the exhaust duct. Both the light source and the photocell are open to the environment of the test room. The cylindrical light beam passes through openings at the top and bottom of the duct, with the resultant light beam centered on the photocell. The test method was developed by Al Steiner, at Underwriters Laboratories [33] for traditional building materials, and exposes samples 7.3 m long and 0.5 m wide (the sample is wider than the chamber, and sits on a ledge). The output is expressed in terms of relative indices for flame spread (flame spread index, FSI) and smoke obscuration (smoke developed index, SDI), based on the fire properties of inorganic reinforced cement board and red oak flooring, assigned arbitrary values of 0 and 100, respectively. It is common to find requirements (in building codes, such as the International Building Code (IBC, [34]) or NFPA 5000 [35], fire codes (such as the IFC [6] or the Uniform Fire Code [36]) and the Life Safety Code [4]) or in specifications, requirements for Class A (or Class I) performance, which corresponds to a flame spread index of 0-25 and a smoke developed index of 0-450.

Only one material caused flashover in the room-corner test, namely the varnished pine, for which all flashover criteria were exceeded. However, several materials released significant heat and smoke. Table 8 presents the major heat release results of the NFPA 265 tests conducted, and Table 9 presents the major smoke release results obtained during the same tests. Average optical density can be calculated by averaging all the OD values or (more correctly) by averaging rate of smoke release and volumetric flow rate; in the latter case average optical density is the average smoke release rate divided by the product of 2.303 and the average volumetric flow rate. Table 10 presents the FSI and SDI values for each material. It should be noted that the varnished pine planking did not qualify as a Class A material, based on its flame spread. Clearly, heat release is the most important property measured in the room-corner test, and only low heat release rates guarantee that flashover will not occur, since increased heat (or energy) release induces additional burning, and thus more heat release. Moreover, the premise that there is a rough correspondence between low heat release rate and low optical density (as a measure of smoke), is a reasonable first approximation: more smoke tends to be associated with more heat release rate.

Table 8. Major Heat Release Results for Materials Tested in NFPA 265

Material	Pk RHR	Av RHR	THR	Time to Peak RHR
	kW	kW	MJ	s
Ceiling Tile	22	0	0	822
FR Composite Panel	128	23	21	534
Mineral Wool	35	0	0	900
Phenolic Foam	153	63	57	840
Pine: **Flashover**	1460	122	52	354
Polyimide Foam	40	4	4	630
Textile Wall Covering, on Calcium Silicate Board	109	8	7	342
Thermoplastic Sheet	40	0.2	0.2	360
Expanded Vinyl Wall Covering, on Gypsum Board	359	14	13	336
Commercial Vinyl Wall Covering, on Gypsum Board	126	1	2	348

Table 9. Major Smoke Obscuration Results for Materials Tested in NFPA 265

Material	Av OD	Av V_s	TSR	Av RSR	Pk RSR
	1/m	m^3/s	m^2	m^2/s	m^2/s
Ceiling Tile	0.063	1.21	165	0.18	0.3
FR Composite Panel	0.088	1.35	270	0.30	0.6
Mineral Wool	0.066	1.18	167	0.19	0.3
Phenolic Foam	0.060	1.27	180	0.20	0.4
Pine: **Flashover**	0.120	1.18	225	0.61	8.5
Polyimide Foam	0.071	1.27	193	0.21	0.4
Textile Wall Covering, on Calcium Silicate Board	0.037	1.78	139	0.15	0.3
Thermoplastic Sheet	0.295	2.00	1359	1.50	7.0
Expanded Vinyl Wall Covering, on Gypsum Board	0.160	1.92	664	0.74	8.9
Commercial Vinyl Wall Covering, on Gypsum Board	0.169	1.67	584	0.65	4.5

Table 10. ASTM E84 Steiner Tunnel Results for Materials Tested

Material	Flame Spread Index (FSI)	Smoke Developed Index (SDI)
Ceiling Tile	15	0
FR Composite Panel	15	15
Mineral Wool	0	0
Phenolic Foam	15	5
Pine	70	105
Polyimide Foam	0	0
Textile Wall Covering, on Calcium Silicate Board	10	10
Thermoplastic Sheet	10	1000
Expanded Vinyl Wall Covering, on Gypsum Board	25	120
Commercial Vinyl Wall Covering, on Gypsum Board	25	80

However, it is also clear that there are some materials that are both much better and others that are much worse in smoke than their heat release results suggest when compared to the general trend. For example, varnished pine causes flashover, but releases much less smoke than would have been expected from materials releasing that much heat. On the other extreme, the thermoplastic sheet releases negligible amounts of heat but high smoke levels.

Table 11 contains results of five series of room-corner tests conducted where heat and smoke were measured. The Table shows that a small fraction of the materials tested for use in construction, approximately 10%, can have adequate heat release (or fire growth) characteristics, but have very high smoke release. In each one of the five series of tests undertaken, there were 1 or 2 materials that would cause a problem if used in buildings; overall a total of 8 out of 84 materials tested were found to be severe outliers and have high smoke.

Table 11: Results of 5 Series of Tests Using Room-Corner Fire Tests

Room-Corner Test Series	Materials Reaching Early Flashover	Materials With Adequate Heat and Low Smoke	Materials With Adequate Heat and High Smoke	# Materials Tested
SwRI [37]	1	8	1	10
Eurefic [38]	14	12	2	28
SBI [39]	12	15	3	30
Coast Guard [40]	3	5	1	9
BFGoodrich [41]	1	5	1	7
Overall	31	45	8	84

References address a study conducted as Southwest Research Institute (San Antonio, TX: SwRI), one in Scandinavia for development of room-corner testing (Eurefic), one in the European Union for development of the Single Burning Item test (SBI), one by the US Coast Guard for analyzing smoke in comparison with heat release and one conducted in Ohio at the BFGoodrich company fire test lab.

NFPA developed a room-corner test specifically designed to assess heat and smoke release of all interior finish (wall and ceiling), other than textile wall coverings, namely NFPA 286 [42]. There is one main difference between NFPA 265 (for textiles) and NFPA 286: the burner. In NFPA 265 the burner is placed 51 mm away from each wall and set at 40 kW and then at 150 kW, while in NFPA 286 the burner is placed against both walls and set at 40 kW and then at 160 kW. This difference means that the flame in NFPA 265 does not reach the ceiling while that in NFPA 286 does. This makes NFPA 286 suitable for all wall and ceiling interior finish, while NFPA 265 is only intended for textile wall coverings. The smoke criterion normally used in the ASTM E84 tunnel test is a smoke developed index (SDI) of 450, and this has been correlated [37] with a total smoke release in a room-corner test of 1,000 m^2. Moreover, an investigation was made to assess the logical threshold criterion for smoke obscuration testing. Several authors have proposed smoke tenability limits as survival criteria. Smoke tenability limits have been measured based on the needed visibility to permit escape and prevent disorientation and, in one case, on the irritancy inherent in smoke. The idea is to allow people present in a fire situation to see far enough that they can escape the fire before being overcome by the effects, of heat or toxicity (or before their eyes become so irritated by smoke that they can no longer see properly). This is usually expressed in terms of visibility distances (in meters), which can then be easily converted to optical density. A value of 4 m visibility, as recommended by Dr. T. Jin for people familiar with their environment [43] seems reasonable and correlates with an average optical density of 0.22 m^{-1} and a total smoke release of 1000 m^2 (or an average smoke release rate of 1.1 m^2/s). This has been adopted by all codes in the USA. This requirement is also consistent with the requirement laid out by the International Maritime Organization (IMO) for testing interior finish materials using the ISO 9705 room-corner test [44]. The maritime requirement is a maximum average rate of smoke release of 1.4 m^2/s, with the ISO 9705 test, which is a more severe test than the NFPA 286 test ["Standard for Qualifying Marine Materials for High Speed Craft as Fire Restricting Materials", IMO Resolution MSC.40 (64) (December 5, 1994), International Maritime Organization, London, UK.)].

More recently, most US codes have made the NFPA 286 room-corner test more severe, by adding a requirement that a material not be permitted to release more than 800 kW, while also permitting textile wall coverings to be tested in the same way as other interior finish materials.

AUTOMOBILES AND VANS

Three vans were purchased and exposed to realistic fire scenarios [45]. In the first test, a van was positioned on a concrete pad, in an exterior location, and tested with the passenger and driver door windows rolled down 3/4 of the way. The test was followed with 26 K-type air thermocouples, positioned inside the van, and 4 video cameras. A shallow aluminum pan with gasoline (50 mL) was placed on the floor under the dash on the passenger side of the van. An additional 20 mL of gasoline were poured onto three sheets of crumpled newspaper. The newspapers were placed beneath the dash on the passenger side of the van. The gasoline pool was ignited with an ignitor. The second test simulated a post-collision fire inside a van, to look at the propensity of materials in the passenger compartment to ignite, burn and propagate fire, and to investigate time available until conditions inside the vehicle became untenable. The van was modified (by: 1) removing the front windshield, 2) removing the top portions of the rear side windows, 3) displacing the roof of the van forward so the front of the headliner was directly above the dash, 4) displacing the dash upward in the center, and 5) placing the engine cover approximately 15 mm back from the dash) to simulate a specific scenario and positioned on a concrete pad, at an exterior location. A small ignition source was placed below the dash area in the vicinity of the engine cover under the transverse HVAC duct. The test was followed with 24 K-type air thermocouples and 5 video cameras. The engine of the van was started and run for ca. 30 min before starting the demonstration. After stopping the engine, the fuel tank was filled with acetone and water to remove residual flammable gasoline and displace any vapors. A diffusion type burner was made from a 6 mm diameter flexible copper tube, extending outside the van, and mounted to the engine beneath the dash and engine cover. Propane gas was fed to the copper tube burner with Tygon tubing from a small cylinder. The propane gas flame was applied with a flame height of 25 mm from the burner surface. The propane supply was turned off once sustained burning was achieved. Eventually, the fire was manually extinguished. In the third test, a different post-collision fire scenario inside another van was investigated. The van was modified (by: 1) removing the front windshield, 2) removing the rear side windows, 3) displacing the roof of the van forward so the front of the headliner was directly above the dash, 4) displacing the dash upward in the center, and 5) placing the engine cover approximately 15 mm back from the dash) and positioned on a concrete pad, at an exterior location. A small ignition source was placed below the dash area in the vicinity of the engine cover. The test was followed with 25 K-type air thermocouples and 6 video cameras. The engine of the van was started and run for approximately 30 min before starting the demonstration. After stopping the engine, the fuel tank was filled with acetone and water to remove residual flammable gasoline and displace any vapors. A diffusion type burner was made from a 6 mm diameter flexible copper tube, extending outside the van, and mounted to the engine beneath the dash and engine cover. Propane gas was fed to the copper tube burner with Tygon tubing from a small cylinder. The propane gas flame was applied with a flame height of 25 mm (1 in.) from the burner surface. The propane supply was turned off once sustained burning was achieved. Eventually, the fire was manually extinguished.

The major qualitative results of the real-scale car tests are indicated below, with the time lines of events shown following each description.

Test 1: The temperature recorded at the headliner near the windshield rapidly increased to a maximum temperature of 782°C at 200 s after ignition while the back portion of the front bench seat reached a maximum temperature of 446°C at 340 s after ignition. The temperature profiles of the thermocouples in the HVAC vents show that fire spread through the central HVAC ductwork traversing the passenger compartment. Examination of the interior of the van after fire extinguishment showed that all combustible materials, including plastic dash components, HVAC duct, carpeting, seat fabric, door panels and the headliner, were damaged in the fire. The fire damage on the passenger door panel and seat was more extensive than the damage on the driver door and seat. The fabric on the exposed surfaces of the bench seats was burned and the exposed foam decomposed. The plastic components of the dash on the passenger side were totally consumed in the fire. The driver side dash components, including the instrument panel, were consumed or exhibited severe melting and charring.

Time line (min: s)	Event
0:00	Ignition of gasoline inside the van.
0:42	Flames are visible inside the center HVAC duct.
0:50	Smoke begins to vent from the two HVAC vents on the top and in the center of the dash.
1:52	Passenger compartment fills with smoke.
2:00	Flames emerge from HVAC vent on the face of the dash on the passenger side. Underneath the passenger dash is fully involved.
2:50	Smoke begins to vent from the air supply vents directly in front of the windshield on the exterior of the van.
3:10	Flames emerge from passenger side window.
3:40	Front windshield compromised.
4:00	Passenger compartment fully involved.
5:30	Van fire extinguished manually.

Test 2: The temperature on the headliner directly above the dash reached a temperature of 699°C at 230 s after ignition. The headliner thermocouple temperature data indicates that the fire spread from the front to the rear of the van in approximately 30 s, once the headliner became involved in the fire. The passenger compartment of the van was already fully involved approximately 160 s after the start of the demonstration.

Time line (min: s)	Event
0:00	Ignition.
1:56	Dash fire.
2:17	Fire from dash impinges on headliner. Headliner dripping.
2:40	Front portion of van fully involved.

2:54	Rear bench seat in flames.
3:03	Fire emerges from rear side windows.
3:20	Side window on driver's side compromised from heat.
3:27	Side door windows compromised from heat.
3:44	Van fire extinguished manually.

Test 3: The temperature on the headliner directly above the dash reached a temperature of 862°C at 335 s after ignition while the back and seat portions of the front bench seat reached a maximum temperature of 866°C at 380 s after ignition. The temperature on the passenger side edge of the dash reached a maximum of 460°C, at 335 s, and that on the HVAC vent, under the dash on the driver side, reached a maximum of 537°C at 360 s after ignition. The headliner thermocouple temperature data indicates that the fire spread from the front to the rear of the van in approximately 40-50 s, once the headliner became involved in the fire. The passenger compartment of the van was already fully involved approximately 5 min after the start of the demonstration.

Time line (min: s)	**Event**
0:00	Ignition.
2:00	Smoke emerges from passenger side HVAC vent.
3:30	Fire grows under dash and emerges from passenger side HVAC vent and out of space between engine cover and dash.
3:50	Top of the dash in flames.
4:20	Fire from dash impinges on headliner. Headliner debris falls from roof.
4:30	Dash fully involved.
4:40	Headliner on fire.
5:00	Front passenger seat in flames.
5:10	Flames out the side rear window space. Van fully involved.
5:34	Side door windows break.
5:45	Van fire extinguished manually.

Analysis of Real-scale Van Tests: In all 3 real-scale tests conducted, fires inside the passenger compartment consumed virtually all the combustible materials, leaving a rusted interior with seat frames and springs and the metal frame of the dash. They also burnt off the vehicle paint. Considering that human tenability ceases when temperatures reach 60°C , heat fluxes reach 20 kW/m^2 and smoke layers get to 1.2 m from the ceiling, this happened no later than 1 min 52 s in test 1 (passenger compartment filled with smoke), or than 2 min 40 s in test 2 (front portion of vehicle fully involved) or than 4 min 40 s in test 3 (after dash is fully involved in fire, the headliner catches fire), so that clearly the vehicle interior became rapidly untenable in all cases. Figures 3 and 4 show traces of temperatures in the headliner, duct and front car seat, illustrating how rapidly high temperatures were reached. Thus, a vehicle occupant who may still be conscious, but is likely to be stunned or otherwise injured, has very little time left to exit or be rescued before receiving fatal injuries as a result of the fire. Such time available for escape or rescue could clearly be increased if the fire performance of the materials in the passenger compartment were improved, for example by better fire retardance [46].

The information presented expands on analyses conducted earlier, that showed that car interior materials exhibit poorer fire performance than average plastics [47-48]. The most interesting issue is that the median fire test data from those cone calorimeter tests conducted on automotive materials was much poorer than that of commercial plastic materials of the same vintage [26], in virtually all aspects of fire performance. Furthermore, car seats perform as poorly (or worse) than domestic fabric-foam seat composites, using non fire retarded foams. In fact, such padding materials would not be permitted for use even in homes in the United Kingdom [16]. Other products with poor fire performance are: the engine cover, the ducts and the headliner. The engine cover should offer a high degree of protection so that ignition, if it occurs at all, is delayed for very long periods and a fire does not penetrate from the engine compartment into the passenger compartment. Thus, it is interesting to note that the molded fiber reinforced plastic material comprising the engine cover in a car studied exhibited fairly poor fire performance. It consisted of two materials, one of which ignited in the cone calorimeter at ca. 2 min at an incident heat flux of 25 kW/m^2, and at ca. 1 min at an incident heat flux of 40 kW/m^2, with a high peak rate of heat release, close to 300 kW/m^2. This offers a simple passageway for flames from the engine compartment to enter the passenger compartment, which can result in a severe fire that traps the passengers, as they are often injured, as a result of collision, and have lower mobility. The fire performance of the duct materials, which was tested in every vehicle investigated, is very poor and could easily be improved by the use of existing fire retarded polyolefin materials. Ducts are surrounded by a large mass of other combustibles, most of which are easily ignitable. Thus, they can cause an untenable situation within a very short time. Vehicle headliners are typically coated fabrics, with a thin covering layer and a back coating (often a foam), perhaps mounted on plywood or fiberglass. This acts, of course, as the interior ceiling finish of the vehicle's passenger compartment. The headliners tested had times to ignition ranging from 9 to 62 s, at a cone calorimeter incident heat flux of 25 kW/m^2; so that they clearly offered little protective escape time! Moreover, in each of the three real-scale fires conducted, headliner temperatures quickly reached values that correspond to well over 50 kW/m^2 incident heat fluxes (approximately 695 °C): headliner ignition would have resulted.

GARBAGE CANS

Typical garbage cans are made of polyethylene without fire retardants. In order to have a reasonable idea of what kind of fire safety issue is involved, the author conducted a full-scale test with a typical household garbage can. It was a polyethylene household garbage can, nominally designated at 30 gallons (114 Liters), which weighed 10.2 kg. The ignition source used was some paper and a match, and the test was conducted in a standard ASTM room (as described above). The test was terminated by manual extinguishment when flashover was reached. The test results indicate that a peak heat release rate of 1.342 MW was obtained at 11.35 min (which simply means that this is when the test was terminated, because the polyethylene was still burning vigorously), the total heat released was 201.4 MJ, the total smoke released was 202 m^2, the peak smoke release rate was 4.2 m^2/s, the mass loss (by weight after the test) was 61.05% and the peak optical density was 3.95 [49]. As a result of this test, and of tests with the cone calorimeter on polyethylene samples, codes in the United States have developed requirements that basically ban polyethylene garbage cans from hospital and other health care environments, by requiring the materials of construction of the cans to meet a heat release rate of 300 kW/m^2 at a flux of 50 kW/m^2 in the cone calorimeter. Table 12 shows some cone calorimeter data on the material (all tests were conducted on commercial polyethylene, non fire retarded) in the horizontal orientation, with sample thicknesses of 6 mm).

Table 12: Cone Calorimeter Data on Polyethylene [26]

Incident Heat Flux	Time to Ignition (s)	Peak Heat Release Rate (kW/m^2)	Total Heat Released (MJ/m^2)
20 kW/m^2	403	912	162
40 kW/m^2	159	1408	221
70 kW/m^2	47	2735	228

CHILDREN'S PLAYGROUND

In recent years there has been a proliferation of children's playground structures, constructed indoors, especially in shopping malls, fast food restaurants and transportation terminals (typically airports). These playgrounds are intended for young children, so that all exposed surfaces are soft and brightly colored. These structures can be fairly large and tend to contain large amounts of combustibles. The typical exposed combustibles are:

- Rigid plastics (usually non fire retarded polyethylene)
- Foam padding, for structural use, usually covered by a textile
- Foam padding for tubes and pipes
- Foamed ball pool balls
- Various fabrics

The potential for such children's playground structures to represent a serious fire hazard for the children using them was investigated by conducting fire testing of one such structure [49] in a standard "ASTM" room (as described above). The structure tested was a "mini children's playground structure", just small enough to fit into the room, constructed of materials all of which were described as complying with ASTM F 1918 [50] (although this was not independently verified by tests on the materials). The structure was erected over concrete floor, without placing any protective surfacing underneath. The test structure weighed approximately 215.5 kg and was built in place, with the following components, with most of the rigid plastics being non fire retarded polyethylene (other than the foams, the polycarbonate and the netting):

- 27.4 m of steel pipe, to construct the 1.2 m x 1.2 m frame
- 35 pipe fittings
- 17 m of "Tuff Pad" foam "post padding"
- 2.4 m of "No-climb" netting
- 1 elbow tube, 760 mm in diameter, 90 degree angle
- 1 T-tube, 760 mm in diameter
- 1 Hexagonal shoe rack
- 1 Triangle platform climb deck
- 1 Tower panel
- 1 Retro Flange
- 1 JC 30 Polycarbonate bubble window
- 160 in-line tie-wraps

The source of ignition used for the test was a standard over-the-counter disposable lighter and 750 g of a standard daily newspaper. The paper was placed sheet-wise in one corner of the test structure and two crumpled balls of paper were placed between the two tubes. No paper was placed inside any of the components and no paper was attached to any part of the structure using artificial means. No accelerants were used. The newspaper was quickly consumed and the hexagonal shoe rack spread the fire further. Abundant white smoke was generated within less than a minute of the ignition of the newspaper. The fire grew slowly over the first several minutes of the test in terms of visible flame spread. However, temperatures at the ceiling directly over the test specimen rose to over 100°C approximately 1 min into the test and never dropped below that level. As the polyethylene from the shoe rack dispersed and the heat of the fire grew, fire spread to the 90 degree elbow tube. Once the fire broke through the elbow tube, flaming drips soon followed, with fuel pools of molten polyethylene, creating a situation of imminent hazard As the pooling and dripping expanded from the consumption of the 90 degree tube, the fire breached that tube and jumped to the upper T-tube. Once this tube, a thinner walled part, ignited, the severity of the flames and the fire hazard increased very rapidly. Flashover occurred in approximately 16 min, roughly 4 min after the breach to the upper levels and thinner walled parts. When the test room flashed over, it produced upper layer and doorway temperatures in excess of 800°C and 700°C, respectively. The heat flux at the floor peaked at over 25 kW/m^2 and the carbon monoxide and carbon dioxide concentrations in the exhaust duct peaked at 43 and 308 g/s, respectively. The test was terminated after approximately 17 minutes. Smoke remained thin and white for the first third of the test; however, as more fuel became involved, oxygen levels dropped in the test room and the smoke developed quickly into a thick black cloud. See major test results in Table 13.

Table 13 - Major Fire Test Results from Children's Playground Fire

Property Described	**Value and Units**	**time (min, s)**
Flashover	Flames Out Door	16 min 7 s
Peak Heat Release Rate	5209 kW	17 min 38 s
Average Rate of Heat release	458 kW	
Peak RHR (30 s average)	4732 kW	
Total Heat Released	467 MJ	
Peak mass loss rate (30 s avg)	148 g/s	16 min 48 s
Average mass loss rate *	13 g/s	
Total Mass Loss*	12 kg	
Peak Smoke Production Rate	16.11 m^2/s	17 min 8 s
Peak Smoke Production Rate (60 s avg)	10.41 m^2/s	
Average Smoke Production Rate	0.96 m^2/s	
Total Smoke Released	982 m^2	
Peak Optical Density	1.08 1/m	16 min 53 s
Exhaust Duct Flow at Pk OD	2.47 m^3/s	16 min 53 s
Average Optical Density	0.098 1/m	
Average Volumetric Exhaust Flow	1.96 m^3/s	
Peak Heat Flux to the Floor	25.8 kW/m^2	17 min 8 s
Peak Average Ceiling Temperature	805°C	17 min 13 s
Peak Doorway Temperature	741°C	17 min 18 s
Peak CO Production Rate	37.61 x 10-3 m^3/s	17 min 3 s
Peak CO Release Rate	43.07 g/s	
Peak CO$_2$ Production Rate	0.171 m^3/s	17 min 28 s
Peak CO$_2$ Release Rate	308 g/s	

* Load cell signal was lost prior to peak heat release rate due to burning on the floor

Flashover was observed because all 4 of the following criteria were met: rate of heat release exceeding 1 MW, flames out the door, floor heat flux exceeding 25 kW/m^2 and temperature rise exceeding 600°C. The test data highlighted are critical for fire hazard: (1) heat release rates above 1 MW correspond to flashover conditions; (2) human skin cannot tolerate temperatures above 65°C for any significant time period before causing irreversible damage and incapacitation; (3) temperatures above 100°C result in human lethality; (4) temperatures above 650°C ensure flashover; (5) total smoke release of 1,000 m^2 is the limit of acceptability for the smoke released by interior wall or ceiling finish in a room the same size in US codes, (6) visibility inside the structure soon fell below 1 m, and (7) survival by children in that structure would have been very difficult (if not impossible) after 1-2 minutes. Moreover, the melting and flaming drips, very early in the test, of structures usually placed on combustible rubber mats, increases the hazard to the children inside. Personal experience with these structures found people crawling through the tubes to reach small children stranded in a remote area of the structure because the child was unable to climb a rope, the only way to exit that area. In case of a fire, the plastics that these structures are built from would create hot fires and heavy smoke that would hinder egress by users and rescue by staff and/or parents. Typical sprinkler activation in such structures may not be enough to protect the children, because of the inability of sprinklers to penetrate zones "protected" by horizontal steel surfaces (needed for structural support). A recent fire in such a structure in a fast food restaurant (in the middle of the night) destroyed the entire restaurant, fortunately without loss of life as the place was closed.

A standard performance specification, ASTM F 1918 [50], exists for these structures. Unfortunately there is no legal requirement that manufacturers comply with this performance specification. Moreover, there are, unfortunately, no code requirements as yet, since these playground structures are not considered to be kiosks, interior finish or decorations (all of which have to meet certain fire safety rules). Work is underway to try to include some appropriate requirements into some codes.

CHRISTMAS TREES AND DECORATIVE LIGHTS

Christmas trees can generate severe fires, and this has been investigated in detail by several projects, in particular work by Gordon Damant [51] and by David Stroup [52]. If the Christmas tree is either: (a) a natural Christmas tree which is wet (that is if the tree has been kept with plenty of water in the roots) or (b) if the tree is an artificial poly(vinyl chloride) (PVC) tree, the tree itself is very difficult to ignite. On the other hand, fire tests conducted on natural Christmas trees (ranging in height from 2.3 to 3.1 m, and dried after 2-3 weeks inside a house) showed that dry Christmas trees can ignite easily and result in fires with heat release rate values of 1.7- 5.2 MW [51], more than enough to ignite any item of upholstered furniture that is close by, for example an easy chair, a couch, or a bed. Moreover, with such a big fire, it is very likely that flashover will be reached in the room of any house very quickly, since 1 MW tends to be enough to cause flashover in a small room. Other fire tests have given similar results, including demonstrations showing that a natural Christmas tree can become fully involved within 7 to 10 s of starting the fire [53]. Of added interest is the fact that in many cases (and the United States has had an average of 8-14 fire fatalities per year from such Christmas tree fires [54]) the actual cause of Christmas tree ignition are the decorative lights which are almost always present [53]. Such lights tend to have very poor fire performance and, more importantly, are often made of materials with inadequate temperature ratings, so that they often thermally degrade after prolonged use, creating weak spots where fires can start. Many regulations exist for such decorative lights, but they are often manufactured in places where requirements are being flaunted and are incorrectly labeled. To compound the potential cause for concern with decorative trees, recently patents have been taken out to start manufacturing polyethylene trees, without using fire retardants. In response to this concern, the Uniform Fire Code (NFPA 1) [36] has added an annex note into the 2006 edition that recommends testing artificial Christmas trees in public occupancies by releasing < 100 kW when tested with a 340 g wood crib furniture calorimeter (UL 1975 [59]) or have small flames when exposed to 450 g of shredded newspaper (UL 511 [60], now withdrawn).

In terms of regulations for these products, this is well underway: (a) natural Christmas trees are not permitted (in the US) in most public occupancies, (b) decorative lights used in public occupancies must be listed (which ensures a high degree of safety if properly done) and (c) decorations (including natural and artificial vegetation) is starting to be considered as a key product the fire safety of which needs to be regulated (for example using a standard fire test being developed, based on the "furniture calorimeter".

TELEVISION SETS

This work was primarily conducted by Jürgen Troitzsch [55-56], who has shown that non fire retarded television sets, such as those commonly used in Europe, can quickly take a room to flashover. The key fire test was carried out with a TV set purchased in Germany, with a 20 x 20 mm hole cut in the lateral right front side of the backplate adjacent to the housing, where a solid fuel pellet (0.15 g, 40-55 W, 5-10 mm flame) was applied. After ignition, the solid fuel pellet flame impinged on the backplate on top of it and later on the edge of the housing, simulating an external and internal low intensity ignition source. Just 24 s after ignition of the pellet, the backplate began to burn. After 1 min, the flames were 8-10 cm high and after 2.5 min they were 1 m high. A pre-flashover situation developed in 4.5 min and complete room flashover, with all the furniture burning, after 7 min with flames 6-8 m high coming out of the front of the fire room. Temperatures rose to 800-900°C and reached over 1,100°C near the ceiling after 12 min. The fire safety requirements for the cabinet of that TV set was no more than a UL 94 HB test [57]. In contrast, TV sets purchased in the US and in Japan, where the cabinets have to meet UL 94 V requirements (Class UL 94 V2, V1, V0 or 5V), either did not ignite or extinguished quickly when exposed to ignition sources as high as 200 mL of isopropanol or cloth soaked in isopropanol (representing up to 40 kW insults).

PREDICTION OF COMPUTER HOUSINGS

In a recent study [58], five engineering thermoplastics were considered for use as computer housings, and a cone calorimeter was used to assess their fire performance. The plastics considered were all materials with the appropriate mechanical and electrical properties and they were all fire retarded to some extent, but their level of fire performance ranged widely. The results were used, by applying a simple zone fire model, to investigate the resulting fire hazard in three fire scenarios: (1), a home fire, with the fire starting at the computer, placed in the kitchen and (2) a home fire (in the same home), with the fire starting at the computer, placed in a bedroom, and (3) a small office building fire, with the fire starting at the computer, placed in one of four offices. The cone calorimeter tests were conducted at an incident heat flux of 50 kW/m^2, in the horizontal orientation. The first analysis assessed the time until the smoke layer reached a level that could be considered untenable. The second analysis conducted evaluated evacuation and tenability. It was very interesting that the relative rankings of four of the materials varied considerably depending on the analysis conducted, but that one of the materials was consistently the safest material in every case. The analysis permitted a ranking of the five materials on the basis of their fire safety as computer housing materials for real use.

CONCLUSIONS AND RECOMMENDATIONS

It is clear from the work discussed here, which covered a wide variety of products, that full-scale fire testing of consumer products is a worthwhile endeavor. In many cases, adequate fire safety information cannot be obtained unless such tests are conducted. When the results of full-scale tests are shown publicly, they can often open up the eyes of regulators and the public to the potential for fire safety concerns that most people never think of.

The advantage of conducting large-scale tests is that they are more likely to be convincing and to generate conclusive results, that can results in changes in requirements or in favorable outcomes in product liability cases (in the USA).

Unfortunately, full-scale tests are very expensive and can usually be conducted only in special scenarios, which makes them lack some generality (it is always possible to argue that the scenario was not perfect or the ignition source too severe). It is usually critical to ensure that such full-scale tests are not conducted to try to replicate an exact situation, as they are never perfectly known, but to understand the real fire performance of the product under investigation.

It is now, of course, possible to make excellent predictions of results of full-scale fire tests (albeit in very simplified scenarios) from small scale fire tests (such as the cone calorimeter) and modeling. In the initial stages of a fire investigation or of research into a fire problem, it is always preferable to attempt to start conducting such small-scale tests and modeling, so that the full-scale tests are properly designed and give the answers needed (which are, of course, not always those that the researcher would have predicted or preferred).

In The United States, three major transport regulatory authorities have conducted full-scale fire tests in recent years: Federal Aviation Administration (which bases its regulation of aircraft materials on them), Coast Guard (which made recommendations to the International Maritime Organization for fire restricting materials based on them) and Federal Railroad Administration (which permits alternate approvals for passenger rail vehicle materials based on them).

In the European Union, three major projects have been conducted in recent years, including full-scale fire tests, looking at fire safety issues:

(1) construction products, which has led to regulation throughout the European Community;
(2) upholstered furniture, which has not led to regulation, and
(3) electrical cables, which is under discussion now for use in regulation.

It is hoped that authorities having jurisdiction will continue paying attention to full-scale tests conducted, either on their behalf or independently by others, and use the results obtained as the basis for regulation of consumer products.

REFERENCES

[1] Hirschler, M.M., "Fire Tests and Interior Furnishings", in *Fire and Flammability of Furnishings and Contents of Buildings*, ASTM STP 1233, Fowell, A.J., Ed., American Society for Testing and Materials, Philadelphia, PA, 1994; pp. 7-31.

[2] Hirschler, M.M., "Use of Heat Release Rate to Predict Whether Individual Furnishings Would Cause Self Propagating Fires", *Fire Safety J.*, 32, 273-296 (1999).

[3] *CA TB 133*, "Flammability Test Procedure for Seating Furniture for Use in Public Occupancies", State of California, Bureau of Home Furnishings and Thermal Insulation, North Highlands, CA, Technical Bulletin 133, January 1991.

[4] *NFPA 101*, "Life Safety Code", National Fire Protection Association, Quincy, MA.

[5] *NFPA 301*, "Code for Safety to Life from Fire on Merchant Vessels", National Fire Protection Association, Quincy, MA.

[6] *IFC*, "International Fire Code", International Code Council, Falls Church, VA.

[7] *ASTM E 1537*, "Standard Test Method for Fire Testing of Seating Upholstered Furniture", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

[8] *CA TB 129*, "Flammability Test Procedure for Mattresses for Use in Public Buildings", State of California, Bureau of Home Furnishings and Thermal Insulation, North Highlands, CA, Technical Bulletin 129, May 1992.

[9] *CA TB 603*, "Requirements and Test Procedure for Resistance of a Mattress/Box Spring Set to a Large Open-Flame", State of California, Bureau of Home Furnishings and Thermal Insulation, North Highlands, CA, Technical Bulletin 603, January 2004.

[10] *ASTM E 1590*, "Standard Test Method for Fire Testing of Mattresses", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

[11] *BS 5852*, "Methods of test for the assessment of the ignitability of upholstered seating by smouldering and flaming ignition sources", British Standards Institution, 389 Chiswick High Road, London, W4 4AL, UK, 1990.

[12] Hirschler, M.M., and Smith, G.F., "Flammability of sets of fabric/foam combinations for use in upholstered furniture", *Fire Safety J.* 16, 13_31 (1990).

[13] *ASTM E 1354*, "Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

[14] *ASTM E 1474*, "Standard Test Method for Determining the Heat Release Rate of Upholstered Furniture and Mattress Components or Composites Using a Bench Scale Oxygen Consumption Calorimeter", Annual Book ASTM Stds, Vol. 04.07, American Society for Testing and Materials, West Conshohocken, PA.

[15] *16 CFR Part 1632*, "Standard for the flammability of mattresses and mattress pads" (FF 5-72, amended), Code of Federal Regulations, Commercial Practices, Subchapter D: Flammable Fabrics Act Regulations, Vol. 16, part 1602-1632, January 1, 1992, pp. 617-636.

[16] *UK Government Consumer Safety Research*, "Effectiveness of the Furniture and Furnishings (Fire) (Safety) Regulations 1988", Consumer Affairs Directorate, Dept. Trade and Industry, London, UK, June 2000 [Research conducted by Professor Gary Stevens, Univ. of Surrey, Guildford, UK].

[17] Emsley, A.M., Lim, L. and Stevens, G., "International Fire Statistics and the Potential Benefits of Fire Counter-Measures", Flame Retardants 2002, February 5-6, 2002, London, pp. 23-32, Interscience Communications, London, UK, 2002.

[18] Hirschler, M.M., "Fire Safety in Detention Environments", Fire Risk & Hazard Assessment Symposium, Fire Protection Research Foundation, June 20-22, 2001, Baltimore, MD, pp. 241-273, NFPA, Quincy, MA.

[19] Hirschler, M.M., "Heat Release Test for Mattresses Intended for Use in Correctional Environments", in Proc. 24th. Int. Conf. on Fire Safety, Product Safety Corp., San Francisco (CA, U.S.A.), Ed. C.J. Hilado, Jan. 12-16, pp. 74-88 (1998).

[20] *ASTM F 1870*, "Standard Guide for Selection of Fire Test Methods for the Assessment of Upholstered Furnishings in Detention and Correctional Facilities", Annual Book ASTM Stds, Vol. 15.01, American Society for Testing and Materials, West Conshohocken, PA.

[21] Hirschler, M.M., "Mattress/Bedding Fires: Statistics and Fire Data Associated with Recent Experience", Fire and Materials Conf., San Francisco, CA, Jan. 22-24, 2001, Interscience Communications, London, UK, pp. 129-140.

[22] Babrauskas, V., personal communication, 2002.

[23] Hirschler, M.M., "Flammability of Mattresses: Recent Fire Test Data and Implications", Business Communications Company Thirteenth Ann. Conference on Recent Advances in Flame Retardancy of Polymeric Materials, June 3-5, 2002, Stamford, CT, Ed. M. Lewin, pp. 280-925, Norwalk, CT, 2002.

[24] Hirschler, M.M., "Residential Upholstered Furniture in the United States and Fire Hazard", Business Communications Company Fifteenth Ann. Conference on Recent Advances in Flame Retardancy of Polymeric Materials, June 7-9, 2004, Stamford, CT, Ed. M. Lewin, pp. 300-315, Norwalk, CT, 2004.

[25] *CA TB 117*, "Requirements, Test Procedures and Apparatus for Testing the Flame Retardance of Resilient Filling Materials Used in Upholstered Furniture", State of California, Bureau of Home Furnishings and Thermal Insulation, North Highlands, CA, Technical Bulletin 117, March 2000

[26] Hirschler, M.M., "Heat release from plastic materials", Chapter 12 a, in "*Heat Release in Fires*", Elsevier, London, UK, Eds. V. Babrauskas and S.J. Grayson, 1992. pp. 375-422.

[27] CBUF Report, "Fire Safety of Upholstered Furniture - the final report on the CBUF research programme", Ed. B. Sundstrom, EUR 16477 EN, European Commission, Measurements and Testing Report, Contract No. 3478/1/0/196/11-BCR-DK(30), 1995, Interscience Communications, London, UK.

[28] Babrauskas, V. and Krasny, J.F., "Fire Behavior of Upholstered Furniture - NBS Monograph 173", National Bureau of Standards, Gaithersburg, MD, 1985.

[29] Damant, G.H. and Nurbakhsh, S., "Heat Release Tests of Mattresses and Bedding Systems", State of California, Bureau of Home Furnishings and Thermal Insulation, October 1991.

[30] Hirschler, M.M. and Janssens, M.L., "Heat and Smoke Measurements of Construction Materials Tested in a Room-Corner Configuration According to NFPA 265", 27th Int. Conf. Fire Safety, Jan. 11-15, 1999, Product Safety Corp., San Francisco (CA, U.S.A.), Ed. C.J. Hilado, pp. 70-93 (1999), San Francisco, CA.

[31] *NFPA 265*, "Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Wall Coverings", National Fire Protection Association, Quincy, MA.

[32] *ASTM E84*, "Test Method for Surface Burning Characteristics of Building Materials", Annual Book of Fire Standards, Amer. Soc. Testing Mater., Vol. 04.07, West Conshohocken, PA.

[33] Steiner, A.J., Method of Fire-Hazard Classification of Building Materials, *ASTM Bulletin*. pp. 19-22 (March 1943), Amer. Soc. Testing Mater., Philadelphia, PA.

[34] *IBC*, "International Building Code", International Code Council, Falls Church, VA.

[35] *NFPA 5000*, "Building Construction and Safety Code", National Fire Protection Association, Quincy, MA.

[36] *UFC*, "Uniform Fire Code" NFPA 1, National Fire Protection Association, Quincy, MA.

[37] Hirschler, M.M. & Janssens, M.L., "Smoke Obscuration Measurements in the NFPA 265 Room-Corner Test", Fire and Materials Conf., San Antonio, TX, Feb. 22-23, 1999, Interscience Communications, London, UK, pp. 179-198.

[38] Ostman, B., Tsantaridis, L., Stensaas, J. and Hovde. P.J., "Smoke Production in the Cone Calorimeter and the Room Fire Test for Surface Products - Correlation Studies", Tratek (Swedish Inst. Wood Technology Research) Report, I 9208053, Stockholm, Sweden, June 1992.

[39] Sundstrom, B., van Hees, P. and Thureson, P., "Results and Analysis from Fire Tests of Building products in ISO 9705, the Room/Corner Test. The SBI Research Programme", SP Report 1998:11, Swedish National Testing and Research Institute, Boras, Sweden, 1998.

[40] Grenier, A.T., Nash, L. & M.L. Janssens, M.L., "Developing Cone Calorimeter Acceptance Criteria for Materials Used in High Speed Craft", Fire and Materials Conf., San Antonio, TX, Feb. 22-23, 1999, Interscience Communications, London, UK, pp. 107-118.

[41] Hirschler, M.M., "Comparison of smoke release data from full scale room tests with results in the cone calorimeter and the NBS smoke chamber", in Proc. Interflam '93, Oxford, UK, March 30-April 1, 1993, pp. 203-212.

[42] *NFPA 286*, Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Wall and Ceiling Interior Finish, National Fire Protection Association, Quincy, MA.

[43] Jin, T., "Studies of Emotional Instability in Smoke from Fires", J. Fire Flammability, 12, 130-142 (1981)]

[44] *ISO 9705*, "Fire Tests - Full Scale Room Test for Surface Products", International Organization for Standardization, Geneva, Switzerland.

[45] Hirschler, M.M., Hoffmann, D.J., Hoffmann, J.M. and Kroll, E.C., "Rate of Heat Release of Plastic Materials from Car Interiors", Business Communications Company Eleventh Ann. Conference on Recent Advances in Flame Retardancy of Polymeric Materials, June 3-5, 2002, Stamford, CT, Ed. M. Lewin, pp. 370-394 , Norwalk, CT, 2002.

[46] Hirschler, M.M., "Fire Retardance, Smoke Toxicity and Fire Hazard, in Proc. Flame Retardants '94, British Plastics Federation Editor, Interscience Communications, London, UK, Jan. 26-27, 1994, pp. 225-37 (1994).

[47] Hirschler, M.M., "Fire Hazard of Automotive Interiors", Fire Risk & Hazard Assessment Symposium, National Fire Protection Research Foundation, June 24-26, 1998, San Francisco, CA, pp. 164-195.

[48] Grayson, S.J. and Hirschler, M.M., "Fire Performance of Plastics in Car Interiors", in Proc. Flame Retardants 2002, Interscience Communications, London, UK, Feb. 5-6, 2002, pp. 197-207.

[49] Hirschler, M.M., "Are Indoor Children's Playground Structures Fire Safe?", Business Communications Company Fifteenth Ann. Conference on Recent Advances in Flame Retardancy of Polymeric Materials, May 23-25 2005, Stamford, CT, Ed. M. Lewin, pp., Norwalk, CT, 2005.

[50] ASTM F 1918, "Standard Safety Performance Specification for Soft Contained Play Equipment", Vol. 15.07, Amer. Soc. Testing & Mater., West Conshohocken., PA.

[51] Damant, G.H. and Nurbakhsh, S., "Christmas Trees - What Happens When They Ignite", Fire and Materials, 18, 9-16 (1994).

[52] Stroup, D.W., DeLauter, L., Lee, J. And Roadarmel, G., "Scotch Pine Christmas Tree Fire Tests - Report of Test FR 4010", National Institute of Standards & Technology, Gaithersburg, MD, December 1999.

[53] Hirschler, M.M., "Fire Hazard Associated with Decorative Lights", Fire Risk & Hazard Assessment Symposium, Fire Protection Research Foundation, July 2002, Baltimore, MD, pp. 283-306, NFPA, Quincy, MA.

[54] Rohr, K.D., "The US Home Product Report (Forms and Types of Materials First Ignited in Fires)", National Fire Protection Assoc., Quincy, MA, December 2001.

[55] Troitzsch, J.H., "Flammability and Fire Behaviour of TV Sets", Presented at the Sixth International Symposium of Fire Safety Science, 5 – 9 July, 1999 in Poitiers, France.

[56] Troitzsch, J.H., "Fire Safety of TV-Sets and PC-Monitors", Report for European Brominated Flame Retardants Industry Panel and European Flame Retardants Association", (2002).

[57] UL 94, Standard Test for Flammability of Plastic Materials for Parts in Devices and Appliances, Underwriters Laboratories, Inc., Northbrook, IL.

[58] Hirschler, M.M., "Fire Performance of Personal Computers and Fire Hazard in a Home and in a Small Office", Proc. Interflam 2004, Edinburgh, UK, July 5-7, 2004, pp. 1383-95, Interscience Communications, London, UK.

[59] UL 1975, Standard for Fire Tests for Foamed Plastics Used for Decorative Purposes, Underwriters Laboratories, Inc., Northbrook, IL.

[60] UL Subject 411, Outline of Investigation for Artificial Christmas Trees (1991), Underwriters Laboratories, Inc., Northbrook, IL.

M.O.I.

PROPOSAL

CPS146

05/01/08

CONSUMER PRODUCT SAFETY
COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Dear Jim,
Following is the quote for the additional parts ordered for the AIS mock-up workstation.

QTY	PRODUCT	DESCRIPTION	SELL	EXTENDED
2.00	S-FDFM36	AIS - AFFORDABLE INTERIOR SYSTEMS FABRIC COVERED FLIPPER DOOR ONLY FOR C SERIES OVERHEAD CABINET, UPH IN T5 SANDY PEBBLE	90.00	180.00
2.00	S-FDBPU36	AIS - AFFORDABLE INTERIOR SYSTEMS ***** Flipper Door Security Panel - 36W	48.80	97.60
	PAINTMA	Paint Grade A		
	RO-P0011	LG - Light Grey		
2.00	A-UNFDED2	AIS - AFFORDABLE INTERIOR SYSTEMS ***** Motion Control Easy Down Mechanism - 24W, 30W, and 48W	41.60	83.20
	PAINTMA	Paint Grade A		
	RO-P0011	LG - Light Grey		
1.00	08-042208-0 2CPS	MOI INSTALLATION DEPT DELIVER AND INSTALL (2) FABRIC COVERED DOORS FOR EXISTING AIS M-WALL C SERIES OVERHEAD CABINETS, 36"W. ALSO INSTALL SAFETY BACKS ON THE EXISTING OVERHEAD CABINETS AND INSTALL THE "EASY DOWN MECHANISMS" ON EACH DOOR	150.00	150.00

M.O.I.

SUBTOTAL....:	510.80
FINAL TOTAL.:	510.80

Thank you for considering MOI, Inc. for this request. If you have any questions, please contact me.

Sincerely,

Gary K Greely

Gary K. Greely/dc
MOI, Inc.

Stevenson, Todd

From: GBHint@aol.com
Sent: Tuesday, May 06, 2008 2:24 PM
To: CPSC-OS
Cc: Ray, Dale
Subject: Upholstered Furniture NPR
Attachments: GBH Attachments 12 to 13.pdf

To: Office of the Secretary, Consumer Product Safety Commission

Please find attached the third part of the attachments to the comments by GBH International on the Upholstered Furniture NPR. A previous e-mail contained the comments.

Yours sincerely

Marcelo M. Hirschler
GBH International
2 Friars Lane - Mill Valley - CA - 94941 - USA
Tel: (415) 388 8278/FAX: (415) 388 5546
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ATTACHMENTS TO

GBH INTERNATIONAL

COMMENTS

MAY 2008

ATTACHMENT 12

Marcelo M. Hirschler[1]

Fire Tests and Interior Furnishings

REFERENCE: Hirschler, M. M., **"Fire Tests and Interior Furnishings,"** *Fire and Flammability of Furnishings and Contents of Buildings, ASTM STP 1233*, A. J. Fowell, Ed., American Society for Testing and Materials, Philadelphia, 1994, pp. 7–31.

ABSTRACT: Interior furnishings are consumer products found in various occupancies. They include furniture, bedding, curtains and drapes, surface finishes (wall, ceiling and floor coverings), and cabinetry. Among the features they have in common is the fact that they are rarely a single material, but that they generally involve various layers. This characteristic is important because it explains why testing of their individual components usually does not give adequate answers.

A survey of the development of such fire tests, and of the present status, is presented here. Special focus will be placed on upholstered furniture tests.

The flammability of upholstered furniture has been under a microscope since it was first discovered to be an important issue, in the late 1960s and early 1970s. However, relatively few tests have been developed and standardized, either in the United States or in other countries. The initial focus was on cigarette ignition and on component testing, resulting in tests such as the NBS mockups and the UFAC test (ASTM E 1352 or NFPA 261 and ASTM E 1353 or NFPA 262, respectively). This was followed by testing of entire chairs with cigarettes (CA TB 116). Eventually, composite component testing with small flames started, pioneered by British standard BS 5852. Parallel to this, material testing continued, using a variety of mostly small-scale tests (the most frequently used tests being CS 191-53 and CA TB 117). In the mid 1980s, tests started to appear for the flaming behavior of complete upholstered furniture items, CA TB 133 being among the most notable ones. The fire community has now understood that the most important fire property is the heat release rate, and this has been incorporated into contents and furnishings tests, as in ASTM E 1537. The next step is the attempt to predict the results of such tests with bench-scale heat release tests and fire models. This work is still in progress.

Fire tests for other interior furnishings have also undergone a complex history, which is reviewed. Tests for the different products are in various stages of development. It would appear that the fire testing of furnishings and contents in the future will entail mostly finished products and heat release equipment.

A flurry of activity is characterizing the present emphasis on furnishings. Moreover, the majority of the new tests being developed generate results that can be used as input for models to carry out fire hazard or fire risk assessments.

KEYWORDS: fire, fire hazard, fire test, flame spread, floor coverings, furnishings, heat release, mattresses, rate of heat release, smoke obscuration, upholstered furniture, wall coverings

Background and History

Interior furnishings and contents is a phrase used very often to describe products in use inside structures, residential or otherwise. However, interior furnishings and contents (or "furnishings" for short) are a very broad umbrella, which covers many products. An analysis of the National Fire Protection Association (NFPA) categories, as contained in NFPA standard 901, turns up more than 45 categories, among the 75 categories of products first

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[1] Safety Engineering Laboratories, Inc., 38 Oak Road, Rocky River, OH 44116.

ignited, which can be classified as furnishings. In whichever form these products are categorized, they are under increasing scrutiny at the main American standards writing organizations: American Society for Testing and Materials (ASTM) and NFPA. Within the ASTM committee on fire standards, E5, subcommittee E5.15, addresses fire and furnishings. NFPA has created two committees specializing in fire and furnishings: the Life Safety Technical Committee on Furnishings and Contents and the Technical Committee on Contents and Furnishings, which have similar (and confusing) names but different responsibilities.

Fire statistics in the United States indicate that furnishings constitute a very large proportion of the fire problem. NFPA fire statistics for 1985 to 1989 show that furnishings are the items first ignited in 40% of all structure fires, and in those fires that cause 40% of all structure fire fatalities [*1*]. The overwhelming majority of the fires and fire fatalities occur in residential environments, but the major headlines (and regulatory attention) address mainly nonresidential construction.

In broad categories, major furnishings of importance in fires are: seating furniture (particularly if it is upholstered), bedding (particularly mattresses), surface finish (wall, ceiling and floor coverings), curtains and drapes, apparel, and cabinetry. They will be dealt with, in that order, in subsequent sections.

A comparison between fire statistics in 1977 to 1978 and in 1983 to 1987 is more startling for similarities than for differences: rankings of the materials in the first few places are very similar (Table 1, [*1*-*2*]). In particular, the two items which dominate the fire fatality statistics in both sets of data are upholstered furniture and bedding: 70 to 80% of the data in the tables (although the statistics have different bases and cannot be compared directly). However, the importance of upholstered furniture and bedding seems to have decreased somewhat over time.

TABLE 1—*Fire statistics in the 1970s and 1980s.*

RESIDENTIAL FIRE FATALITIES BY ITEM FIRST IGNITED (% OF TOTAL)	1977 to 1978	1983 to 1987
Upholstered furniture	43.5	22.9
Bedding	33.0	16.1
Interior wall covering	?	7.1
Floor covering	4.3	3.9
Clothing (worn)	6.0	2.9
Clothing (not worn)	4.7	2.3
Curtains and drapes	2.9	0.9
RESIDENTIAL FIRES BY ITEM FIRST IGNITED (% OF TOTAL)	**1977 to 1978**	**1983 to 1987**
Upholstered furniture	18.5	3.9
Bedding	39.6	7.8
Interior wall covering	?	4.3
Floor covering	3.7	2.3
Clothing (worn)	0.8	0.2
Clothing (not worn)	13.2	2.7
Curtains and drapes	5.1	1.2

NOTE—1977 to 1978 statistics address textile products in structure fires (Tovey and Katz 1981) while 1983 to 1987 statistics address all materials in residential fires (Miller 1991). The latter statistics contain a total of 31 categories, as well as unknown (or "others"). The major items first ignited in 1983 to 1987 residential fires not in the table are: rubbish (15.7%), cooking materials (14.0%), structural members (7.8%), wire and cable (6.8%), as well as "others" (14.1%). The major items first ignited in 1983 to 1987 residential fire fatalities not in the table are: structural members [illegible] flammable liquids (6.6%), as well as "others" (8.9%).

Upholstered Furniture

Background

It is important to understand that, although upholstered furniture is the largest single product first ignited leading to fire fatalities, it is still only one of many causes. When the focus of fire statistics is restricted to upholstered furniture alone, it is the item first ignited in only 2.8% of all structure fires, in the 1985 to 1989 time period, corresponding to 15.6% of all fire fatalities [*1*]. In residential environments, upholstered furniture is the item first ignited in 3.4% of all fires, corresponding to 16.3% of the fire fatalities. If all residential fires are excluded, upholstered furniture represents the item first ignited in only 1.4% of fires and 5.8% of the fire fatalities.

It should be noted that the majority of upholstered furniture fires result from ignition by smoking materials, with a strong emphasis on cigarettes. The relative contribution of cigarettes varies according to the source of information. They may contribute ca. 65% of the total [*3*] or 77% of the total, in the 1980 to 1984 period [*4*]. Fires initiated by cigarettes are smouldering fires, but they can easily (after varying times) transition into flaming fires.

In 1982, cigarette initiated fires caused about 30% of all fire deaths in the United States [*5*], of which over 80% are residential. However, they were responsible for only 10% of all residential fires. This indicates that the mortality rate of such fires is very high. The overwhelming majority (70 to 80%) of all cigarette initiated fires start in upholstered furniture or bedding. In 1982, 20.1% of all civilian fire fatalities in the United States started with the ignition of upholstered furniture [*6*–*7*]. Smoking materials igniting upholstered furniture in residences were responsible for starting the fires resulting in 16.5% of all civilian fire fatalities during that year [*5*].

In the intervening years, cigarette initiated upholstered furniture fires and fire fatalities have decreased. Table 2 contains information, gathered by the Upholstered Furniture Action Council (UFAC), on fires and fire fatalities, with particular emphasis on upholstered furniture in residences, in the years 1978 and 1989 [*8*]. The decreases in all categories can be attributed, at least partially, to two causes: more extensive scrutiny of products by manu-

TABLE 2—*Fires and fire fatalities related to upholstered furniture.*

	1978	1989
FIRES		
Total residential fires	757 500	513 500
Total upholstered furniture fires	43 000	18 600
Smoking materials	28 000	9 700
Open flames	7 900	4 200
Others	7 100	4 700
FIRE FATALITIES		
Total residential fires	6 840	4 440
Total upholstered furniture fires	1 600	890
Smoking materials	1 300	670
Open flames	200	130
Others	100	90

facturers before being offered for sale and a higher penetration of smoke detectors. However, recent statistics still find that, in the 1984 to 1988 period, 27.9% of all fire fatalities result from fires started by smoking materials [*9–10*].

The flammability of upholstered furniture has been a major concern in the United States since the late 1960s, and became a federal issue with the 1967 amendments to the Flammable Fabrics Act of 1953 (see Section on Apparel).

Ignition by Smoking Materials

On 29 Nov. 1972 the Federal Register stated, on behalf of the Department of Commerce, that a flammability standard or other regulation might be needed for upholstered furniture. The emphasis was to be placed on ignition of furniture by smoking materials, particularly cigarettes. The technical work was started at the National Bureau of Standards (NBS, today National Institute of Standards and Technology, NIST). When the Consumer Product Safety Commission (CPSC) was established in May 1973, it was given the authority to deal with the issue. A private organization, UFAC, was created in 1974, as a voluntary industry association to focus on the problem of the flammability of upholstered furniture. Its funds come from the majority of the large furniture manufacturers producing upholstered furniture for the residential market, many of whom belong to the American Furniture Manufacturers' Association (a trade association). Thus, during the mid to late 1970s, parallel work was being carried out in the public and in the private sector, to develop tests to prevent ignition by cigarettes, that is, smouldering ingition. The public sector work was being done at NBS and the private sector work at Guilford Laboratories (Greensboro, North Carolina), on behalf of UFAC.

Both efforts culminated in test methods. NBS developed a test for cigarette ignition of upholstered furniture mockups in 1976. This test was eventually standardized both by NFPA (NFPA 261, 1983) and ASTM (ASTM E 1352, 1989). UFAC developed their series of six test methods for cigarette ignition of upholstered furniture components and constructions somewhat later, but the voluntary program went in effect in 1978. CPSC decided, in 1979, to defer implementation of mandatory federal regulation while it monitored UFAC activities, a position still in effect today. These test methods were also standardized at ASTM (ASTM E 1353, 1989) and NFPA (NFPA 260, 1983). Precision and bias statements for ASTM E 1352 and E 1353 were developed in 1993, following a round robin for both tests, carried out through joint work between ASTM E5.15 and ASTM D13.52.

The State of California, at the California Bureau of Home Furnishings (CBHF), passed Technical Bulletins 116 [*11*] and 117 [*12*], which required compliance, respectively, with cigarette ignition of full items of upholstered furniture and with cigarette and flaming ignition of furniture components by October 1977. Today they are applicable to all upholstered furniture items offered for sale in the state of California: TB 116 on a voluntary, basis while TB 117 is a requirement. Manufacturers of contract furniture (that is, nonresidential) are mostly associated within the Business and Institutional Furniture Manufacturers' Association (BIFMA). They have adopted the NBS mockup test as a voluntary standard (BIFMA X5.7, part 5), as well as a small flame test: the 45° angle test for apparel (incorporated into BIFMA X5.7, part 4, into CA TB 117, for fabrics and other components, and CS 191-53, see Section on Apparel, for fabrics only).

The development of furniture resistant to cigarette ignition has meant that the materials used, particularly for fabrics, have changed. The trend was to move away from materials which smoulder easily to materials which do not smoulder. Thus, lightweight cellulosic materials (like cotton, linen, or rayon), have been replaced mostly by synthetic materials, unless they have been treated with fire retardants. These synthetic materials (thermoplastics) tend to shrink away from the flame and are, thus, much more likely to resist ignition by cigarettes. However, the same thermoplastic materials which do not smoulder, may be ignited easily by small flames.

The introduction of the cigarette ignition tests have resulted in a very large decrease in the preponderance of some extremely flammable fillings, such as sisal, kapok, jute, or untreated cotton, from furniture offered for sale commercially. Some of the more flammable polyurethane foams are also no longer used in commercial furniture. However, the UFAC test requires that the foam filling be tested under a fabric which passes the cigarette ignition test. Thus, it is possible for foams to have relatively poor fire performance and yet pass the test because they are covered with a fabric that resists smouldering.

Flaming Ignition Sources

The first serious attempt at developing a flaming ignition standard for upholstered furniture systems was a British Standard (BS 5852, part 2, [*13*]), developed as a consequence of a famous 1979 furniture store fire in Manchester, United Kingdom. This test uses a variety of wood cribs, and it tests a combination of fabric and filling made up into two standard cushions: bottom and back. The wood cribs range from No. 4, weighing only 8.5 g, to No. 7, weighing 126 g. A recent study showed that the "rankings" resulting from testing fabric/foam combinations in this test correlated well with those that could be obtained from using the cone calorimeter at $25\ kW/m^2$ [*14*]. Over the last few years, the standard has been modified somewhat, so that testing for qualification is now done effectively on separate items. Fillings are qualified when tested under a "standard" flame retarded polyester fabric, and fabrics are qualified when tested over a filling deemed acceptable. Thus, it is not required to test the system actually proposed for use, which is likely to be less satisfactory than testing finished systems.

In the United States, in order to address the issue of flaming ignition, independently, CBHF and the Boston Fire Department (BFD), started developing fire tests for flaming ignition of seating furniture: California Technical Bulletin 133 [*15*] and the Boston chair test. These tests were designed for very high risk furniture. In fact, the test under the jurisdiction of CBHF became applicable, in 1992, to seating furniture in institutions, hospitals, mental health facilities, health care facilities, nursing homes, board and care facilities, convalescent homes, child day care centers, public auditoriums, stadiums, and public assembly areas of hotels, motels, or lodging houses containing ten or more articles of seating furniture, with an exception allowed if they are fully sprinklered. The BFD test had somewhat similar applicability, except that Boston generally does not give the same exceptions for sprinklers.

In May 1984 CBHF issued the first version of TB 133. This test involved burning a full item of seating furniture, inside a room of specified dimensions (12 by 10 by 8 ft high (3.7 by 3.1 by 2.4 m high)), using as flaming ignition source a wire cage, containing five crumpled double sheets of newspaper. In order to pass the test, the item could not exceed a series of six criteria, involving temperature increase, smoke obscuration, carbon monoxide generation, and weight loss (Table 3). A survey of the number of failures indicated that the vast majority of failures involved one or both of the temperature increase criteria [*16*]. This is illustrated in Fig. 1. In the meantime, the test has been modified several times, but the basic concept remains the same. The crucial change resulted from cooperative work between CBHF and NIST [*17–19*]. It has been shown recently that the most important fire property is the rate of heat release [*20*]. This ties in well with the concept that the main failure criteria are based on energy increase. Thus, the NIST/CBHF work focussed on three aspects: (*a*) find a heat release rate corresponding to the temperature increase in the upper layer of the

TABLE 3—*Failure criteria for CA TB 133; January 1991.*

No.	Measurement	Value	Location
		CRITERIA A (NO HEAT RELEASE)	
1	Temperature increase	≤200°F	ceiling thermocouple
2.	Temperature increase	≤40°F	4 ft thermocouple
3.	Smoke opacity	≤75%	4 ft monitor
4.	Carbon monoxide	≤1000 ppm; 5 min	top corner monitor
5.	Weight loss	≤3 lb; 10 min	
		CRITERIA B (HEAT RELEASE)	
1.	Peak heat release rate	≤80 kW	duct measurement
2.	Total heat release	≤25 MJ; 10 min	duct measurement
3.	Smoke opacity	≤75%	4 ft monitor
4.	Carbon monoxide	≤1000 ppm; 5 min	top corner monitor

NOTE—

The original criteria included a smoke opacity criterion of ≤50% smoke opacity at a floor monitor, and stated that carbon monoxide concentration was not to exceed 1000 ppm continuously for 1 min.

Approximate conversion factors between SI units and actual criteria: 1°F = 9/5 °C (with zero shifted 32 °F); 1 lb = 0.4536 kg; and 1 ft = 0.3048 m.

room, (*b*) find a more reproducible ignition source than the newspaper, and (*c*) understanding whether there is a difference between tests carried out in different rooms. The results were: the 200°F (111°C) increase in temperature can be modeled by a 80 kW heat release rate and the newspaper ignition source can be modelled by a square propane gas burner, with a gas flow of 13 L/min for 80 s. The research also showed that the heat release rate is not affected by the size and shape of the room, within certain limits, if the heat release rate does not exceed 600 kW [*18*].

The state of California adopted a new version of TB 133 in January 1991, which requires the use of the square gas burner. It allows the measurement of temperature increase or of heat release rates as pass fail criteria. In order to pass the test a furniture item has to avoid exceeding any of the following four criteria: heat release rate of ≤80 kW, total heat release of ≤25 MJ in the first 10 min (both in the exhaust duct), ≤75% smoke opacity at a smoke obscuration monitor located at 4 ft (1.2 m) from the floor and emit ≤1000 ppm carbon monoxide for a 5 min period, at a room monitoring location (Table 3). TB 133 also allows testing in a "furniture calorimeter," that is, under a hood, rather than inside a room, where the first two requirements only can be met. If heat release is not measured, the test criteria needed to pass TB 133 include temperature increases of ≤200°F (111°C) at a ceiling thermocouple, ≤50°F (28°C) at a 4 ft (1.2 m) thermocouple and weight loss of ≤3 lb (1.36 kg) in the first 10 min. TB 133 has now relegated the newspaper source to the status of a screening test only. It has also been announced that room measurements will no longer be acceptable beyond the fall of 1993.

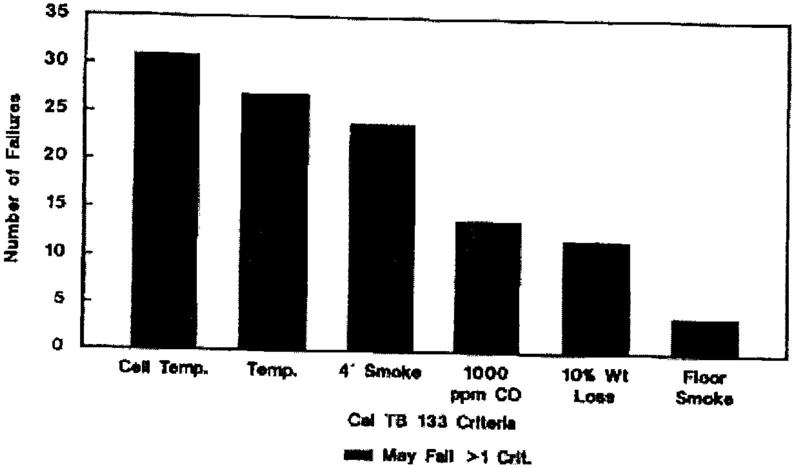

FIG. 1—*Failures in California Technical Bulletin 133. Number of failures out of 93 chairs tested up to 1990 (they may fail more than one criterion).*

It is worth mentioning an interesting study that compared the performance of five upholstered furniture systems in three tests: CA TB 133 (without heat release), BFD, and BS 5852 (crib 7), and showed similarities and differences [*21*].

ASTM has now developed a version of California TB 133: ASTM E 1537, with three main differences. First, ASTM E 1537 offers three equal alternatives: the "ASTM room" (2.4 by 3.7 by 2.4 m high), the California room (3.7 by 3.1 by 2.4 m high) and a furniture calorimeter; TB 133 recommends the use of the California room, while allowing the other alternatives. Second, ASTM E 1537 requires smoke obscuration and gas (carbon monoxide and carbon dioxide) measurements in the exhaust duct, whereas TB 133 requires measurements in the room for them, but only if the heat release measurements are made in the room. Third, ASTM E 1537 has *no* pass/fail criteria, while TB 133 does (Table 3). ASTM E 1537 is also much more detailed in equipment description, calibration, use, the theory behind it, and limitations, than TB 133.

CBHF managed a preliminary round robin of the test, in mid-1992. Unfortunately, the laboratories had dissimilar facilities: in fact only some of them were capable of measuring heat release, and the round robin results were inconclusive and disappointing. The publication, in the meantime, of a "Code of Practice," by CBHF, as well as of ASTM E 1537, will aid in ensuring that laboratories will have detailed procedures to follow. Thus, a new round robin should have a more satisfactory outcome and may also be useful for the development of precision and bias statements for ASTM E 1537.

Another full-scale test for flaming ignition of upholstered furniture exists: the furniture calorimeter. This name is given to a test where the item of furniture is placed on a load cell, underneath a hood. Heat, smoke (and potentially toxic gas) release is measured in the exhaust duct, while mass loss can also be measured. There is *no compartment in which the item to be tested is placed.* Thus, the compartment is considered of infinite size, so that the walls cause no radiation effects. Consequently, test results are due entirely to the item tested. Measurements of temperature, smoke obscuration, or toxic gases in a room cannot be made when using a furniture calorimeter. This is, normally, of no consequence, since room measurements are of little or no value for fire hazard assessment, since small differences in measurement location can result in large differences in output. A furniture calorimeter is more satisfactory to measure heat release rates of furniture burning intensely, at heat release rates well over 600 kW, but room size and shape do not affect the results at lower heat release rates. Work by NIST/CBHF showed that differences between furniture calorimeter and room heat release results start to differ only at heat release rates above 600 kW (if the item is burning in a corner, or even higher if the item is burning in the center) [*18*]. Thus, the added expense of building a very large room in order to house a furniture calorimeter yields no significant advantage. The only United States standard for fire tests on upholstered furniture to date is UL 1056, the first edition of which was issued in 1989, using a 3/4 lb (340 g) wood crib as ignition source. It is likely to be amended to replace the wood crib by a gas burner.

Furniture Requirements in Codes

There never has been a mandatory national standard for fire testing in the upholstered furniture area, partially because of the preponderance of residential furniture compared to furniture used in public occupancies. However, some state and local authorities have implemented mandatory flammability requirements, the most comprehensive one being that adopted by California (see Section on Ignition by Smoking Materials). At present, too, the NFPA Safety to Life Code (NFPA 101, 1991 edition [22]) contains provisions (31.1.4.2) for testing upholstered furniture to determine their resistance to cigarette ignition, as tested according to NFPA 260 and NFPA 261 (Class I components in NFPA 260 and char length less than 1.5 in. (38 mm) in NFPA 261), which is deemed unnecessary by the code if an approved automatic sprinkler system has been installed. This does not apply to residential occupancies, assembly occupancies, educational occupancies (which include day care centers), mercantile occupancies, or business occupancies. The use of NFPA 261 applies to health care occupancies (31.4.5.2), detention and correctional facilities (31.5.4.2), and board and care homes (31.7.5.2), and is recommended for corridors or similar areas in nonsprinklered hotels, dormitories, or apartment buildings (A31.6.6).

NFPA 101 also made a very significant change in its 1991 version: it introduced heat release requirements for upholstered furniture (and mattresses). The requirements in the code are not very stringent. However, it is the first time that a heat release rate requirement has been adopted by an NFPA code. Section 31.1.4.3 specifies a peak heat release rate for a single item of upholstered furniture of no more than 250 kW (unless the facility has either smoke detectors or automatic sprinklers) or 500 kW (unless the facility is sprinklered). It further requires total heat release not to exceed 75 MJ in the first 5 min of the test (unless the facility is fully sprinklered). In the 1994 version of NFPA 101, the requirements will be tightened: the exemption for smoke detectors is eliminated and limits will be set at 250 kW and 40 MJ. This applies only to detention and correctional occupanices (31.5.4.2) and is recommended for health care occupancies (A31.4.5.2) and board and care homes (A31.7.5.2). The original requirements were put in based on the basis of maintaining a tenable environment in the room of origin (250 kW) or avoiding flashover in it (500 kW) with a single item of furniture burning. Many states adopt NFPA 101, but it often takes several years before the most recent version is actually in use.

Two of three model building codes have no flammability requirements for furniture: those developed by the Building Code and Administrators International (BOCA, the Basic/National Building Code, used mainly in the Northeast) and by the International Conference of Building Officials (ICBO, the Uniform Building Code, effective in the Western states). However, the third one, namely, the Southern Building Code Congress International (SBCCI, the Standard Building Code, valid mostly throughout the South) adopted a requirement of a peak heat release rate of 500 kW for hospitals and nursing homes without automatic sprinklers, as well as the NFPA 260 cigarette test. The code also contains, in appendices, requirements based on NFPA 260 and 261 and on CS 191-53 (see Section on Apparel). These requirements, however, are for guidance of local ordinances only.

Prediction of Full-Scale Fire Test Results

It is always desirable to have a small-scale test which can predict the results of the full-scale one. If the small-scale test does not do that, it serves little useful purpose. It has been shown that results from the cone calorimeter can be used to predict results of full scale chair burns, because the cone calorimeter measures heat release, smoke release, ignitability, and weight loss [3,18]. Both the cone and the OSU rate of heat release calorimeters are suitable for testing fabric/foam combinations for heat release [14,23–24]. Moreover, the results of both rate of heat release instruments correlate with one another [23,25–26]. Therefore, both ASTM and NFPA have developed standards to use the cone calorimeter for testing upholstered furniture components, destined for high risk applications: ASTM E 1474 and NFPA 264A. In both cases the incident heat flux is 35 kW/m². If the 3 min average heat release rate is less than 100 kW/m², the furniture item is unlikely to cause a self propagating fire and, thus, to fail the full-scale test [18]. However, the cone calorimeter tests could be modified potentially by using a less intense heat source so as to make them more relevant to residential furniture, where a 25 kW/m² heat flux has been shown in two studies to be satisfactory [14,23].

Stacking Chairs

Stacked stacking chairs are also under investigation at ASTM. A task group of ASTM Subcommittee E5.15 is working closely with CBHF, a fire testing laboratory and some furniture manufacturers to develop a flaming source test, based mainly on heat release requirements. The investigation addressed the type of gas burner, the flame intensity (gas flow rate), the duration of the ignition source (40 to 100 s), and the number of chairs in the stack (3 to 7). After the preliminary investigation, it was decided to use a T-shaped burner (the same one used for mattress testing, see Section on Bedding) and a flame gas flow rate of 12 L/min. The recommendations by both testing organizations were that a gas flame duration of 80 s and a stack of 5 chairs would serve the purpose of identifying the undesirable products. Adoption of an ASTM standard is still likely to be some time away.

Bedding

The flammability requirements for bedding (which for most practical purposes means mattresses) closely follows that for upholstered furniture. Having stated this, it should be mentioned that the addition of other bedding products (sheets, blankets, pillows) may make a substantial difference to the overall heat release. There are federal requirements, which involve the cigarette ignition of mattresses, mattress tickings, and mattress pads (Department of Commerce (DOC) FF 4-72, or Code of Federal Regulation (CFR) 1632 [27]). This test, as amended, went into effect in 1985.

CBHF developed TB 121, which has newspaper under the mattress as the ignition source in 1980 [28] and the first draft version of TB 129 (with a gas burner as the ignition source), equivalent to the new version of TB 133, in 1992 [29]. In TB 121, a set of 10 double sheets of newspaper (185 g) is placed in a galvanized metal container at the geometric center and beneath the bottom mattress surface. The failure criteria are: >10% weight loss in the first 10 min of the test, a temperature of 500°F (260°C) at a thermocouple beneath the ceiling and above the mattress and a carbon monoxide concentration of 1000 ppm at any point in the test room. The failure criteria for TB 129 are similar to those for TB 133 (see Table 3), but the peak heat release rate allowed is 100 kW. It appears that TB 121 is more stringent than TB 129, which is why it is still applicable to very high risk occupancies, such as correctional institutions. Both ASTM and NFPA are developing versions of TB 129. The gas burner used is a T-shaped burner rather than a square burner, and the gas flow is 12 L/min, for a period of 180 s. A furniture calorimeter standard also exists for mattresses: UL 1895. NFPA 101 requirements for mattresses are identical to those for upholstered furniture. It has been shown that the cone calorimeter can also be used as the small-scale predictive test for this application [*30*].

Wall Coverings

The flammability of wall coverings has been regulated in many countries for years. This has caused considerable discomfort to the fire science community, since there is no correlation at all between the results of those old fashioned tests. In 1973 Howard Emmons [*31*] published a comparison between the rankings of 24 wall coverings according to the methods used in six European countries. The results are shown in Fig. 2: a scattergun would have given equally good predictability.

The traditional means by which wall coverings are tested in the United States is the long familiar "Steiner tunnel" test, ASTM E 84. The test requires burning a 24 ft by 20 in. (7.3 m by 51 mm) sample (although pieces can be lined up in series) lining the roof of a tunnel, and exposed to a 300 000 BTU/h (about 90 kW) methane gas flame for 10 min. The results are expressed in terms of an index, based on the arbitrary decision that 23/32 in. (18.3 mm) select grade red oak flooring sheets have an index of 100 and that 0.25 in. (6.4 mm) inorganic reinforced cement boards have an index of 0.

However, wall coverings frequently have very low thickness and low mass. Anomalies are common where wall coverings achieve excellent results in the Steiner tunnel test, without offering an adequate degree of fire protection. In fact, it was found that many textile wall coverings meet Class A (flame spread index ≤25) requirements in the Steiner tunnel test but cause flashover when tested in a room corner scenario [*32–33*], in a study for the American Textile Manufacturers' Institute (ATMI) (Table 4). The scenario used was the Williamson screening test [*34*]. In some cases a fully lined room was used, which is in fact a standard test, Uniform Building Code UBC 42-2 test [*35*], now also adopted by NFPA, as NFPA 265 (Standard Fire Test for Evaluating Room Fire Growth Contribution of Textile Wall Coverings).

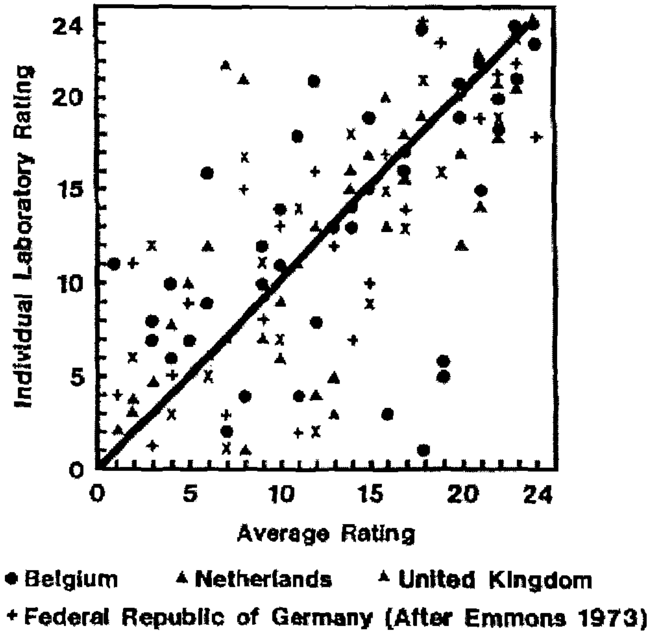

FIG. 2—*Flammability of wall coverings: individual laboratory rating and average rating, according* [illegible] *the standard test used in 6 countries.*

The tunnel test is very severe, but, unfortunately, it is also known to have poor reproducibility. Furthermore, false positives are very common, that is, it is possible to manufacture products in such a way as to appear not to spread flame in this test, without actually improving their fire performance in a real fire. The test is unsuitable for materials which melt or drip, because they may not burn simply because they are no longer exposed to the flame. They would then appear not to spread flame nor release smoke, giving the false impression of being safe. The test is also unsuitable for very thin materials. The test can also give false negatives, particularly in terms of smoke emission because of its unrealistic fire model. Attempts to correlate the flame spread results from the tunnel with those of full-scale room

TABLE 4—*Results of corner room tests run by ATMI.*

Test No.	Material	Pk RHR, kW	THR, MJ	Ceil T, °C	Floor Flux, kW/m²	E84 FSR	Time Peak, s
6	G	83	10.1	272	2.2	25	510
7	AA	684	30.6	672	17.7	15	510
8	O	207	8.3	365	6.5	15	520
9	Qfr	310	9.0	388	7.5		520
10	BB	93	9.5	269	2.5		510
11	C	62	2.2	237	2.1		510
12	B	207	5.8	342	5.3		525
13	Zfr	142	3.3	293	3.6		510
19	Lfr	182	13.0	448	6.6	15	510
20	R	587	51.1	582	19.3	15	550
21	H	46	5.4	297	2.3		510
22	L	227	20.2	404	7.1		510
23	O[a]	297	21.2	369	4.4	15	510
24	PWfr	366	23.0	672	10.6		1090
26	R[a]	5771	228.1	929	150	15	580
28	Q[a]	497		553	8.1	15	520
29	Q[b]	474		642	9.3	15	520
30	Q[a]	928		763	24.5	15	520
31	R[b]	590		590	13.4	15	550
32	R[a,b]	331		542	4.9	15	520
33	H[b]	160		405	2.3		520
34	C[b]	119		326	1.8		540
35	B[b]	298		477	5.3		540
36	PP-95[a]	337		567	5.3		520
37	PP-PF[b]	1166		785	26.6		530
38	DD[b]	249		477	4.7		580
39	113-9[b]	309		578	7.3		520
40	113-9[a]	728		765	20.9		600

EXPLANATION—Pk RHR: peak rate of heat release (in kW), THR: total heat released (in MJ), Ceil T: Ceiling temperature (in degrees centigrade), Floor Flux: radiant flux to the floor (in kW/m²), E 84 FSR: flame spread rating in the Steiner tunnel test (ASTM E 84), Time peak: Time to reach peak rate of heat release, in s.

[a] Fully lined room (FLR); UBC 42-2.

[b] 2-ft (0.6 m) wide samples

fires usually have failed, although the test does seem reasonably well suited for wood products. Thus, its results really cannot be used for fire hazard assessment or for good fire safety choices.

The Uniform Building Code refers to two full-scale room corner tests (UBC 17-5 [*36*] and UBC 42-2 [*35*]) applicable to wall lining materials. The former test really was designed for foam plastic insulation, but can also be used for wall linings. Two other tests have been developed for full room testing of wall linings: one has been under consideration at ASTM for several years and one is an international standard (ISO 9705 [*37*]). The former has undergone a 1992 round robin for precision and bias development. Table 5 compares these various tests and the Williamson screening test.

In view of the known deficiencies of the Steiner tunnel test (ASTM E 84) several efforts have been made to investigate whether other small-scale tests can be used to predict full-scale fire test results. It is worth mentioning in particular a study where many of the ATMI wall coverings were tested in the cone calorimeter (ASTM E 1354) and in the lateral ignition and flame spread test (LIFT, ASTM E 1321, [*38*]). Unfortunately, the results of both tests (Tables 6 and 7) could not immediately give the same ranking of materials, and further work is needed to understand fully the degree of correlation with the full-scale tests.

An international effort (EUREFIC) culminated in 1991, whereby the predictability of various tests was considered, with regard to the international room corner standard (ISO 9705) [*39*]. The tests under consideration were traditional reaction to fire tests in three of the major European countries: France (Epiradiateur, NF P792-501 [*40*]), Germany (Brandschacht, DIN 4102 Part 1 [*41*]), and Great Britain (surface spread of flame apparatus, BS 476, Part 7 [*42*]). The correlation of the rankings between the small-scale and full-scale tests

TABLE 5—*Comparison of full-scale room corner tests.*

	ASTM Proposed	UBC 42-2	ISO 9705	UBC 17-5	Williamson
Room Size	8 by 12 by 8 ft	8 by 12 by 8 ft	2.5 by 3.7 by 2.5 m	8 by 12 by 8 ft	8 by 12 by 8 ft
Doorway			Symmetrical, opposite central test wall		
Igniter	gas burner	gas burner	gas burner	wood crib	gas burner
Location	against wall	2 in. off wall	against wall	1 in. off wall	2 in. off wall
Sample	3 walls	3 walls	3 walls + ceiling	3 walls + ceiling	wall section 1 or 2 ft wide
Amount	256 ft^2	256 ft^2	36.5 m^2	352 ft^2	46 ft^2 *
Testing					
Duration	15 min	15 min	20 min	15 min	15 min
Intensity					
Initial	40 kW	40 kW	100 kW	30 lb wood	40 kW
Duration	5 min	5 min	10 min	15 min	5 min
Final	160 kW	150 kW	300 kW	none	150 kW
Duration	10 min	10 min	10 min	...	10 min
Measurements					
RHR	yes	yes	yes	no	yes
Floor flux	yes	yes	yes	no	yes
Ceiling T	yes	yes	yes	no	yes
Smoke Obsc.	yes	no	yes	yes	no
CO	yes	yes	yes	no	no
CO$_2$	yes	yes	yes	no	no
Visual	yes	yes	yes	yes	yes

COMMENTS—UBC 17-5 requires that "inside of room" is that dimension.

Other tests use a standard room, and line walls (and ceiling if needed).

Approximate conversion factors between SI units and actual criteria: 1 ft = 0.3048 m; 1 in. = 2.54 mm, and 1 ft^2 = 0.0929 m^2.

ISO 9705 test has other alternatives, but this is the preferred one.

* For 1 ft wide strips, for the 2 ft wide strips the area is 64 ft^2.

TABLE 6—*Test results for ATMI samples in the cone calorimeter.*

Material	Cone 30 Pk RHR	Cone 50 Pk RHR	Cone 30 THR	Cone 50 THR	Cone 30 TTI	Cone 50 TTI	Cone 30 TTI/RHR	Cone 50 TTI/RHR	Cone 30 Pk MLR	Cone 50 Pk MLR	Cone 30 Burn time	Cone 50 Burn time
G	70	73	2	2	240	50	3.4	0.7	9	7	15	22
AA	233	252	21	25	105	40	0.5	0.2	12	8	152	132
Q	140	225	3	7	205	60	1.5	0.3	8	16	28	35
Qfr	169	213	3	8	220	75	1.3	0.4	10	12	25	42
C	108	124	4	5	100	50	0.9	0.4	10	11	20	23
B	137	247	2	6	205	60	1.5	0.2	9	8	23	27
R	43	288	3	9	370	60	8.6	0.2	4	12	43	52
H		105		4	60		0.6			6		30
PP-PF	209	262	8	17	110	70	0.5	0.3	9	8	113	78

EXPLANATIONS—Cone 30 and Cone 50: cone tests at 30 and 50 kW/m^2 incident flux, Pk RHR: peak rate of heat release, in kW/m^2, THR: total heat release, in MJ/m^2, TTI: time to ignition, in s, TTI/RHR: ratio of time to ignition to peak rate of heat release, in s m^2/kW, Pk MLR: in g/s m^2, Burn time: average time of main burn, in s.

TABLE 7—*Test results for AIMI samples in the LIFT apparatus.*

Material	LIFT Q" ig	LIFT T ig	LIFT $k\rho c$	LIFT Q" s	LIFT T s	LIFT ϕ	LIFT b	LIFT Q"e 50
G	20	434	1.04				0.054	30
AA	18.1	386	0.85	7.2	248	27.9	0.053	30
Q	24	473	0.84	6.6	235	25.3	0.065	38
Qfr	24	473	0.86	10.7	305	35	0.064	35
C	20.5	440	0.68	9.9	300	20.6	0.072	35
B	26	491	0.82	12.5	340	33.5	0.068	34
R	24	473	0.87	6.8	240	15.7	0.064	39
H	24.7	480	0.47	16.7	397	15.3	0.069	50
PP-PF	16	386	0.85	7.2	248	27.9	0.053	29

EXPLANATIONS: LIFT Q" ig: critical flux for ignition, in kW/m^2, T ig: ignition temperature, in degrees centigrade, $k\rho c$: thermal inertia, in (kW/m^2 K)^2 s, Q" s: critical flux for spread, in kW/m^2, T s: flame temperature, in degrees centigrade, ϕ: flame heating parameter, in kW^2/m^3, b: ignition parameter, in s$^{-1/2}$, Q"e 50: surface flux at 50 mm, in kW/m^2.

were: 48% for the French test, 37% for the British test, and 61% for the German test. In contrast cone calorimeter rankings showed 94% correlation with full-scale ones (Figs. 3–6). EUREFIC, furthermore, also developed a computer model to predict the time-temperature curve and time to flashover in the full-scale test from cone calorimeter input. These are not simple manual computations.

ASTM E5.15 is working on the development of a standard for the application of the cone calorimeter to wall coverings. In that connection, it is important to consider the fact that

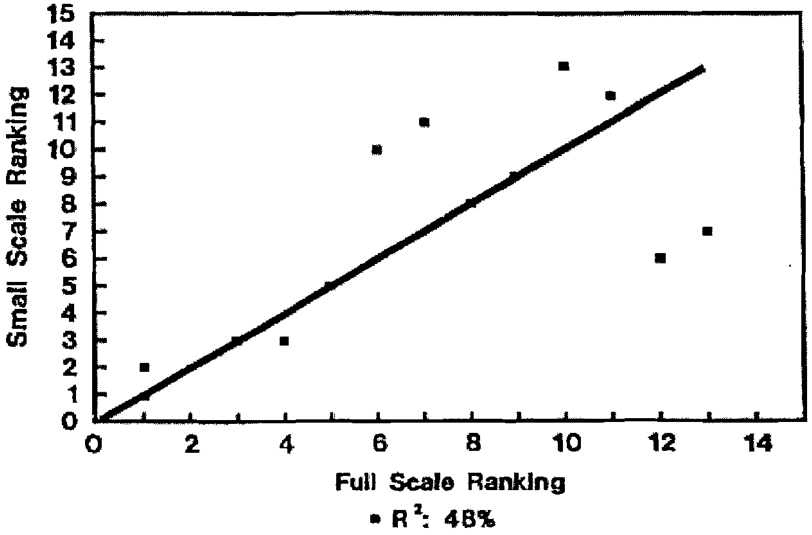

FIG. 3—*Correlation of wall linings between rankings in the full-scale ISO 9705 test and in the French national standard NFP 92-501 (Epiradiateur).*

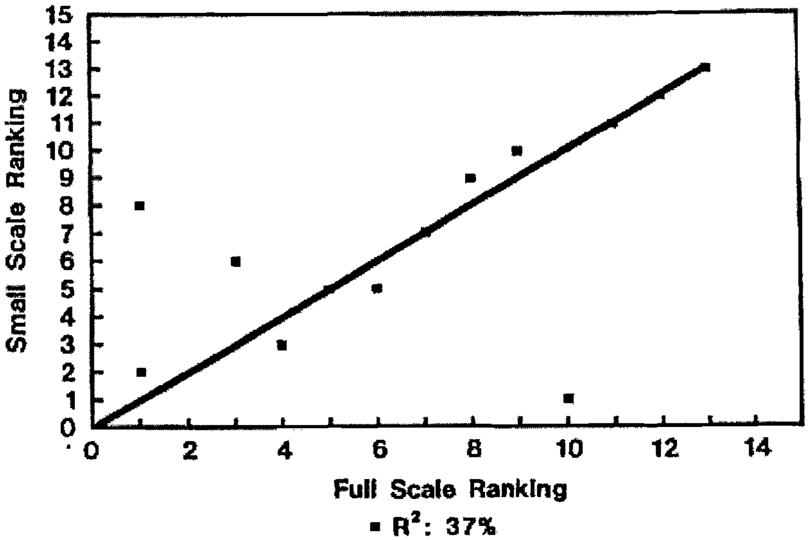

FIG. 4—*Correlation of wall linings between rankings in the full-scale ISO 9705 test and in the German national standard DIN 4102 Pt 1 (Brandschacht).*

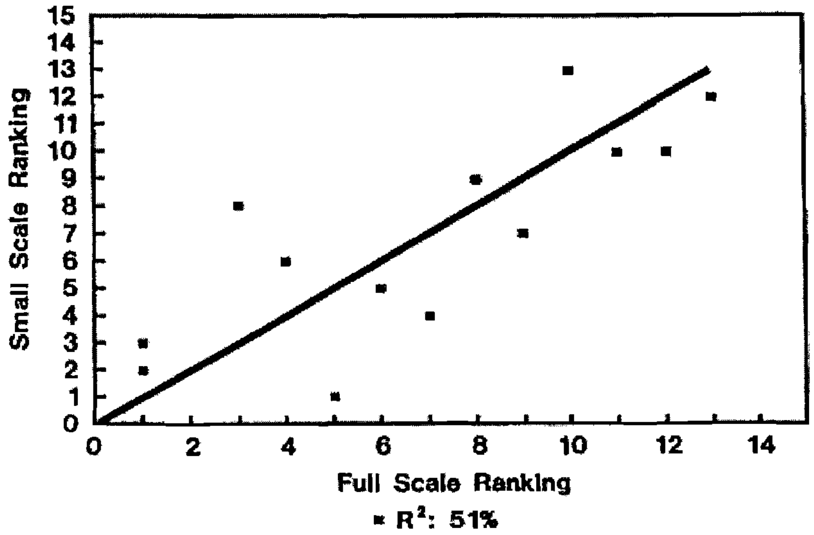

FIG. 5—*Correlation of wall linings between rankings in the full-scale ISO 9705 test and in the British national standard BS 476 Pt 7 (spread of flame test).*

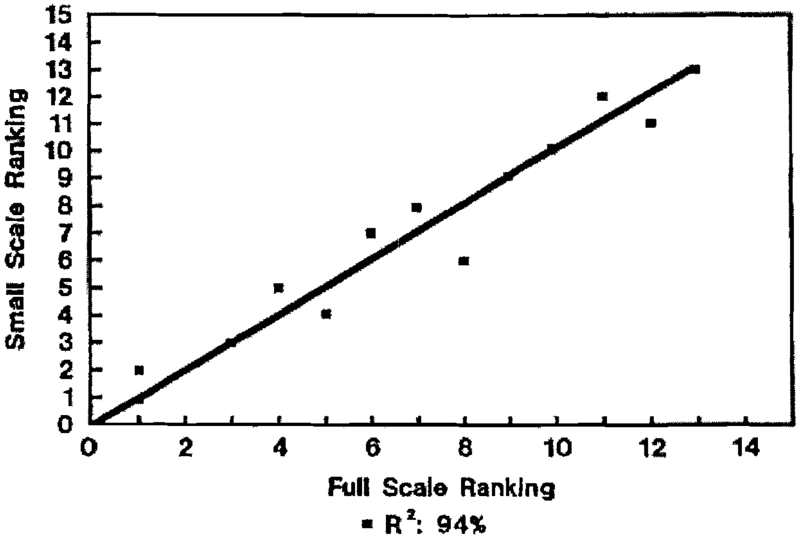

FIG. 6—*Correlation of wall linings between rankings in the full-scale ISO 9705 test and in the cone calorimeter (ISO 5660 and ASTM E 1354).*

the cone calorimeter is recommended for horizontal testing and not vertical testing [*43*], while wall coverings normally are used in a vertical orientation. In view of the work done to date, however, it would appear that cone calorimeter testing is a viable option.

Floor Coverings

The flammability of floor coverings became an issue in the late 1960s, after some serious fires where flames were reported as spreading slowly along carpeted corridors, during the development stages of the fire. The result was the promulgation of Federal Flammability standards DOC FF 1-70 and DOC FF 2-70 (CFR 1630 and 1631 [*44–45*]), addressing flammability of carpets and rugs (and small carpets and rugs). The test, commonly known as "pill" test or "methenamine pill" test, uses a lighted flat methenamine tablet as the source of energy applied to the carpet. CFR 1630 is a mandatory requirement for all carpets sold in the United States; small carpets and rugs need not pass the test, but must carry a large "Flammable" label if they do not. DOC FF 1-70 is mandatory since 1 April 1971. ASTM standardized a similar test (ASTM D 2859) at about the same time (1970). The test is, probably, an adequate measure of ease of ignition when no radiant energy is applied to the carpet.

In January 1970 a serious fire spread along a corridor in a Marietta, Ohio, nursing home, resulting in 31 fire fatalities [*46*]. This, and a few other fires [*47–48*], suggested the need to develop a test for the fire performance of carpets when subjected to a certain incident flux. The first approach was to use the Steiner tunnel test (ASTM E 84), since no other test existed. However, it was soon decided the test was inadequate [*49*] and that a specific flame spread test for floor coverings had to be devised. A few years later, as a result of extensive work at NBS, involving both small- and large-scale fire tests [*50–51*] and a flame spread hazard study [*52*], the concept of critical radiant flux was developed, as a potential measure of the danger associated with carpet flame spread [*53*]. This led to the flooring radiant panel test, which measures the critical radiant flux required to cause a carpet to spread flame along the entire sample distance [*54–55*]; ASTM E 648 (first standardized in 1978). A similar test was also standardized by NFPA (NFPA 253). The test has received some criticism as to its correlation with real-scale fires, since its results do not appear to be adequate to "rank" carpets for their fire performance.

The flooring radiant panel test has undergone considerable scrutiny in recent times. In particular, ASTM recently has developed a modified pilot burner to get more consistent results (ASTM E 648-91, changes not introduced into NFPA 253). However, the modification has been criticized because it makes the test more severe. The test is used extensively for specifications by various agencies, and the NFPA version is quoted in NFPA 101, but it is not a federal flammability standard.

In the international front, ISO and CEN are considering the adoption of the critical radiant flux test for both flame spread and smoke release. In fact, this already has happened in Germany (DIN 4102, Part 14 [*56*]), where a smoke obscuration monitor has also been added, into the exhaust duct. The test has been allocated a work project by CEN [*57*] and a number by ISO (ISO 9239).

In the period since the original development of the flooring radiant panel, several investigations have addressed aspects of fire hazard associated with carpets, after the initial flame spread study [*53*]. The Carpet & Rug Institute financed an extensive study, which shows that the potential toxic fire hazard of carpets and rugs is of no greater consequence than that of any other product burning in a fire [*58*]. More recently, a study for the National Fire Protection Research Foundation Fire Risk Assessment Research Project concluded that carpets, in offices, played no significant role in fire fatalities [*4*]. This is a consequence of two major issues: (1) heat and fire travel upward, and thus away from floor coverings and (2) most carpets in use comply with the federal flammability standards, and are, therefore, relatively difficult to ignite. Thus, existing standards have eliminated successfully most of the "worst actors" formerly present.

However, NFPA fire statistics show floor coverings as the furnishing item first ignited associated with the fourth largest number of fire fatalities (after upholstered furniture, bedding, and clothing) [*59*]. It must be pointed out that materials classified under the category of floor covering include accelerants and other items lying on the floor. When the data are analyzed in greater detail, it is found that carpets and rugs are associated with less than one third of the fire fatalities ascribed to those items first ignited described as floor coverings.

In spite of the relatively low importance of floor coverings to fire hazard, their fire performance is often specified. This may involve the development of ranking classifications using the "pill" test or the flooring radiant panel test. It also may mean using pass/fail criteria based on smoke obscuration, usually via the NBS smoke density chamber (ASTM E 662), or smoke toxicity (as is the case in New York city). ASTM E5 has been in the process of developing a fire hazard assessment standard for floor coverings (especially carpets) for some time, but no consensus exists.

The cone calorimeter has been shown to be an excellent tool for testing the fire performance of floor coverings [*60–64*]. The incident fluxes used tend to be in the range of 25 to 30 kW/m². The references cited have found good correlation between the results of cone calorimeter tests and full-scale tests but that the flooring radiant panel test can give misleading results. Smoke results from NBS smoke chamber were also found inadequate. In this connection, it is worth recalling that the cone calorimeter has been shown to be an excellent instrument for measuring smoke obscuration [*65–66*].

Curtains and Drapes

In 1967, the Flammable Fabrics Act of 1953 was extended to include interior furnishings and other products which might constitute an unreasonable flammability risk. The Flammable Fabrics Act defined interior furnishings as: "any type of furnishings made in whole or in part of fabric and related materials and intended for use, or which may reasonably be expected to be used, in homes, offices, or other places of assembly or accommodation."

The flammability of curtains and drapes was first addressed by the promulgation of the NFPA 701 test in 1969. This standard contains two tests: a small-scale and a large-scale one, both addressing vertical flame spread. The traditional small-scale version for curtains uses a 38 mm methane flame (from a laboratory burner and in a cabinet similar to that in CS 191-53) exposing a 90 by 255 mm sample for 12 s. The large-scale one uses a 280 mm flame exposing a 2.1 m high by 0.6 m wide sample for 2 min. The pass/fail requirements are based on char length and afterglow; no flaming drips are allowed to continue burning.

However, the test, in its original version, did not address multiple layers of curtains. A number of full-scale experiments indicated that full length burning of the curtain, or even flashover, can be reached in a room when combining multiple layers of curtain materials, each one of which will comply with the NFPA 701 test [*67–68*]. In order to avoid the need for full-scale room testing, a new small-scale test was developed, commonly known as the "phone booth" test. In this test, a 150 mm by 400 mm sample (which may contain multiple layers) is exposed to a 100 mm methane flame for 45 s. The pass/fail criterion for this test is based on sample mass loss, with 40% the limit. This test was first proposed for standardization at NFPA, within the umbrella of NFPA 701, in 1992. Some work has been done with the test, including a round robin with nine laboratories, but both its degree of predictability of full-scale fire performance and its reproducibility are still unclear. All three tests are now under consideration at ASTM.

Apparel

Early Attention

The result of the first serious public scrutiny of the flammability of textile furnishings was the standardization of ASTM D 1230 in 1952. Soon afterwards followed the promulgation of the Flammable Fabrics Act in 1953, amended in 1954. The major emphasis at the time was placed on apparel, with the objective of banning "torch sweaters" and highly flammable children's "cowboy chaps." A 45° angle flammability test was thus developed, for apparel fabrics (CS 191-53), which became effective in 1954, and is still valid, as CFR 1610 [*69*]. The two tests, ASTM D 1230 and CFR 1610 are similar, but not identical. The test was not designed to raise the general level of fabric flammability performance. However, in view of the lack of other tests, the federal test has received extensive criticism, because of its mildness, and limitations. A list of limitations of the test has been published [*70*]. These limitations can be summed up in two major ones: (*a*) it does not mirror actual fire conditions and (*b*) virtually every fabric in existence in the 1990s will comply with it. Several authors have suggested that the test can be modified to update it [*70–71*]. It is not clear whether a more stringent test is required, or whether this would simply eliminate many fabrics from sale without added safety benefit. An NFPA study of statistics on products first ignited in residential fires in the 1983 to 1987 period shows that clothing (on a person) is the fifth leading known cause of ignition leading to fire fatalities [*59*], representing 130 deaths/year. In fact, if all clothing is counted together, it moves up to the fourth leading cause, with 237 fatalities/year. Thus, fire fatalities from this cause have not changed ranking since 1977 to 1978, when a previous such study was made [*2*]. In fact, the fire death rate per fire for fires initiated in worn clothing has gone up from 1 in 10 (1977 to 1978) to 1 in 7 (1983 to 1987).

When considering apparel, it must be borne in mind that textile fabrics can be classified broadly into charring and melting. The former are mostly cellulosics, like cotton, or materials like wool, and they tend to propagate flame upwards. The latter are mostly thermoplastics (for example, nylon, polypropylene, and polyester), which shrink away from the flame and may *not* propagate the flame upwards. Thermoplastic fibers are, thus, less prone to cause extensive fire damage, if they are not held tightly in position. Moreover, thermoplastic fibers usually are also resistant to smouldering ignition. However, they are often less resistant to small flaming ignition sources when held in position and prevented from shrinking, unless adequately flame retarded. One exception to this trend are vinyl fabrics, which, although thermoplastic, tend to resist both smouldering and small flaming ignition sources. This issue has been investigated in detail in 1982 by John Krasny [*72*].

It is important to note, too, that combinations of fabrics will, often, perform like the poorer component in the system. Thus, when a thermoplastic is attached to a char former, this will often result in more intense burning than the additive effect of two combustibles of similar characteristics. This is important in lined clothing, and can even be noticed depending on the type of thread used to sew the items. Curiously, however, such combinations can cause more intense fires, but with lower upward flame spread rates.

Children's Sleepwear

Following extensive press coverage of several fire fatalities involving ignition of children's sleepwear in the late 1960s and early 1970s, a test was devised, which would protect small children from the danger inherent in using the then prevalent long loose nightgowns made of non fire retarded cotton. Two federal flammability standards address this issue: DOC FF 3-71 (CFR 1615, for children up to 6 years' old [*73*]) and DOC FF 5-74 (CFR 1616, for children 7 through 14 years' old [*74*]). Both tests are virtually identical. They involve applying a 3.8 cm methane flame, at a 25° angle on a vertical sample for 3 s. In order to pass the test, char length may not exceed 17.8 cm average, or 25.4 cm (under load) for any burn (out of 10). Sleepwear which does not pass the test must be labeled Flammable and displayed separately from the ones that pass the test. This test virtually has eliminated the earlier materials used for children's nightwear. However, in recent years, products are being sold in the United States which look very similar to acceptable nightwear, but are *not labeled* as children's nightwear (and do not pass the test). These products need to meet only CFR 1610. This is one of the most compelling arguments for updating CFR 1610. However, the Consumer Product Safety Commission (CPSC) has proposed, in early 1993, to decrease enforcement of children's sleepwear requirements, in view of the scarcity of serious incidents and the enforcement difficulties.

Protective Clothing

For a long time, thermoplastic fibers were proposed as protective clothing for structural fire fighters. It has now become clear that they are usually inadequate. They have been replaced mostly by aromatic polyamides and polyimides. Standards addressing requirements for the apparel worn by fire fighters have been issued by NFPA: they are NFPA 1971 (protective apparel for structural fire fighting), NFPA 1973 (gloves for structural fire fighters), and NFPA 1975 (station/work uniforms for fire fighters). The materials for the coats are required to be tested by Federal Test Method Standard 191A, Method 5903.1.

This is a vertical exposure to a 38 mm methane flame for 12 s. The pass requirements are an afterflame of less than 2 s and a char length of less than 102 m, with no melting or dripping. Station trousers, exposed to the same test, are allowed a char length of less than 152 mm. Finally, gloves are allowed some after glow (4 s) but a char length of only 25 mm.

Cabinetry

The fire standard that applies to office furnishings is contained in section 18 of UL 1286 (Standard for Office Furnishings) [75]. The second edition was issued in 1988, with some revisions issued in July 1990, none of which addresses fire.

The standard states (section 18.1) that "components of a major part of an office furnishing system or individual unit, and that have an individual or a mechanically contiguous surface of 10 ft^2 (0.93 m^2) or more shall have a flame spread index of 200 or less, and smoke developed index of 200 or less, when tested in accordance with UL 723 (ASTM E 84 or NFPA 255, the Steiner tunnel test). However, there is an exception: no smoke development number is required, provided the result is marked appropriately, in a way visible after installation (see Marking, section 34.4).

Decorative moldings, base raceway covers, shelves, and similar items, when made of combustible material (the standard calls it polymeric) "and is mechanically contiguous across and runs at least the full width of one unit" have to meet simply the V-0 or 5-V requirements of the UL 94 small-scale test. In this test, vertical specimens are exposed to a small laboratory flame. To achieve a V-0 rating, five, 5 in. (127 mm) long, use thickness, specimens are exposed from underneath to a 3/4 in. (19 mm) flame. They achieve a V-0 rating if they do not burn for over 50 s, are completely destroyed, and do not drip so as to ignite cotton placed underneath. For a 5-V rating both bars (5 in. (127 mm) long) and plaques (6 by 6 in. (152 by 152 mm)) are exposed to a 5 in. (127 mm) flame. The bars may not burn for 60 s or drip so as to ignite the cotton. If the plaques have a hole after the burn, the sample is classified as 5-VB, and if not it is a 5-VA.

Both of these tests, UL 723 and UL 94, are well established and ingrained into many codes and regulations. Consequently, the tunnel test is unlikely to be replaced any time soon. The UL 94 test is also required in many specifications of plastic materials (all materials going into small appliances and other electrical equipment parts, for example). It is not particularly indicative of good fire performance, particularly because of the low-intensity fire source, and materials with poor fire performance may yield falsely satisfactory results.

A more modern flame spread test was designed at NIST: the LIFT (lateral ignition and flame spread test, ASTM E 1321, mentioned earlier). It gives data acceptable for fire hazard assessment through modeling. Unfortunately, it has had very limited popularity so far, with only a handful of apparatuses in existence, either in the United States or internationally. It cannot test materials that melt and drip, because the sample is vertical. A modification already exists (HIFT: horizontal ignition and flame spread test) which turns the apparatus 90° and solves that problem. There is, however, even less experience with it.

Another alternative for replacing the tunnel is the use of room corner tests, such as UBC 42-2 (NFPA 265), or others (Table 5). This approach is likely to lead to fruition, because it is based on the idea that the results of such room tests, which measure heat release rate, will soon be predictable from cone calorimeter results. Unfortunately, in the short run, there is still no established test for flame spread adequate for fire hazard assessment. The most famous new test instrument, the cone calorimeter *does not measure flame spread,* although it appears that flame spread can be calculated from some of its results (particularly the inverse of the time to ignition).

ASTM E5 Activities

The subcommittee of ASTM E5 dealing specifically with fire and "furnishings" is E5.15. The ultimate focus of the activities of this subcommittee is the development of fire hazard and fire risk assessment standards. However, since the technology for writing fire hazard assessment standards is still in its infancy, the subcommittee also deals with fire-test-response standards.

It is interesting that this subcommittee developed a standard in 1985 called "Standard Practice for Assessment of Fire Risk by Occupancy Classification," which was published under the number ASTM E 931-85. A detailed history of this standard can be found in "Concepts Behind ASTM E 931," in this volume [76].

The subcommittee also has task groups working on fire hazard assessment of individual furnishings: upholstered furniture, floor coverings, and wall coverings. It is likely that the work will be long term, based on the standard guide for development of fire hazard assessment standards, ASTM E 1546. The most advanced of these potential fire hazard assessment standards addresses carpets and had an unsuccessful subcommittee ballot in early 1992. This ballot was held through subcommittee E5.35, before the activity was returned to E5.15 for further study. A joint task group was then formed, between E5.15 and E5.35, to complete the project.

ASTM E5.15 has responsibility for four standards, as well as E 931, E 1352, and E 1353, for smouldering ignition of upholstered furniture components, by the action of cigarettes, E 1474, for radiant ignition of upholstered furniture or mattress composites in the cone calorimeter and E 1537, for flaming ignition of full-scale upholstered furniture items.

Work is underway to generate fire-test-response standards involving stacked stacking chairs, mattresses, wall coverings, and curtains and drapes. The subcommittee is also considering the development of a test for vandalized mattresses in correctional institutions. Table 8 is a list of the active task groups in the subcommittee and the furnishings issues they are working on.

TABLE 8—*Active task groups in ASTM E5.15 in 1993.*

No.	Rough Title	Chair	Main Subjects
	SUBCOMMITTEE CHAIRMAN: MARCELO HIRSCHLER		
2	Curtains & drapes	John Michener	phone booth test, fire hazard assessment
3	Floor coverings	Andrew Fowell	fire hazard assessment
4	Stacking chairs	Gordon Damant	full scale heat release test of full-scale stacked chairs
5	Upholst. furn.	John Michener	cigarette ignition stds: precision and bias, fire hazard assessment
6	Wall coverings	John Michener	fire hazard assessment
7	E931 Review	Hugh Talley	review of occupancy classification practice
8	Full scale furn.	Marcelo Hirschler	full-scale heat, smoke, and toxic gas release test for upholstered furniture
10	Mattresses	Vytenis Babrauskas	full-scale heat, smoke, and toxic gas release test for mattresses; small-scale test for mattress composites
11	Cone applications	Thomas Fritz	small scale cone calorimeter application to wall coverings
12	Vandalized matt. in prisons	Marcelo Hirschler	search for tests for vandalized mattresses in correctional institutions

Conclusions

The area of furnishings and contents often remains unaddressed by codes or regulations. The reason for this is very clear: many of these products are bought by the consumers and installed in buildings after they have been approved by the code officials.

A relatively large number of standards and tests exist which are used for furnishings and contents. Progress in all areas is not of the same caliber; however, some tests are of a much more advanced nature than others. It is, however, very noticeable that the emphasis being placed on the fire performance of furnishings and contents has increased considerably in recent years. New tests also often emphasize heat release measurements.

Recent progress has involved changing from testing individual materials to testing finished systems or products. The next step, already underway, is to test full-scale systems by determining heat release rate. This must be followed by the use of small-scale tests which can be truly predictive of the fire performance of the full-scale tests. Predictions will, in all likelihood, result from the added use of mathematical fire models. The final step should be the utilization of small-scale test results and mathematical models to predict fire hazard or fire risk in real occupancies.

It is encouraging that the thrust of the majority of new tests being developed and being considered for standardization is that they should be useful to generate results that can be used in fire hazard or fire risk assessment.

References

[1] Hall, J., "Items First Ignited in Fires—1985–1989," Report to NFPA Technical Committee on Contents and Furnishings, National Fire Protection Association, Quincy, MA, 17 Aug. 1992.

[2] Tovey, H. and Katz, R., "Involvement of Textile Products in Structure Fires: Frequency, Consequences and Causes," Fire Retardant Chemicals Association 1980 Fall Meeting, "Flame Retardant Needs of the Future: Building and Construction," Pontevedra Beach, FL, 5–8 Oct. 1980, pp. 131–158.

[3] Babrauskas, V. and Krasny, J., "Fire Behavior of Upholstered Furniture," NBS Monograph 173, National Bureau of Standards, Gaithersburg, MD, Nov. 1985.

[4] Stiefel, S. W., Bukowski, R. W., Hall, J. R., and Clarke, F. B., "Fire Risk Assessment Method: Case Study 2, Carpets in Offices," NISTIR 90-4244, National Institute of Standards Technology, April 1990.

[5] Tinsworth, D. K., "National Estimates of 1982 Fire Losses Associated with Upholstered Furniture," U.S. Consumer Product Safety Commission, 1984.

[6] Karter, M. J., "Fire Loss in the United States During 1982," *Fire Journal*, Vol. 77, No. 5, 1983, p. 44.

[7] Williams, S. S., "Flammability Regulations and Standards in the United States for Upholstered Furniture," Technomic, Lancaster, PA, 1985.

[8] Talley, T. H., NFPA Symposium on Furnishings and Contents, Gaithersburg, MD, Feb. 1992.

[9] Miller, A. L., "Where There's Smoking There's Fire," *NFPA Journal*, Jan.–Feb. 1991, pp. 86–93.

[10] Karter, M. J. and Miller, A. L., "Patterns of Fire Casualties in Home Fires by Age and Sex, 1984–88," National Fire Protection Association, Quincy, MA, April 1991.

[11] "Requirements, Test Procedure and Apparatus for Testing the Flame Retardance of Upholstered Furniture," CA TB 116, State of California, Bureau of Home Furnishings and Thermal Insulation, 3485 Orange Grove Avenue, North Highlands, CA, 95660-5595, Technical Bulletin 116, Jan. 1980.

[12] "Requirements, Test Procedure and Apparatus for Testing the Flame Retardance of Resilient Filling Materials Used in Upholstered Furniture," CA TB 117, State of California, Bureau of Home Furnishings and Thermal Insulation, 3485 Orange Grove Avenue, North Highlands, CA, 95660-5595, Technical Bulletin 117, Jan. 1980.

[13] Fire Tests for Furniture, Part 2. Methods of Test for the Ignitability of Upholstered Composites for Seating by Flame Sources. BS 5852, Part 2, 1988. British Standards Institution, Hampden House, 61 Green Street, London, W1, UK, 1988.

[14] Hirschler, M. M. and Smith, G. F., "Flammability of Sets of Fabric/Foam Combinations for Use in Upholstered Furniture," *Fire Safety Journal*, Vol. 16, 1990, pp. 13–31.

[15] "Flammability Test Procedure for Seating Furniture for Use in Public Occupancies," CA TB 133, State of California, Bureau of Home Furnishings and Thermal Insulation, 3485 Orange Grove Avenue, North Highlands, CA, 95660-5595, Technical Bulletin 133, Jan. 1991.

[16] Damant, G. H., "Flammability of Furnishings: Someone had to be First!," Flame Retardants' 90, Proceedings Flame Retardants' 90, Conference, 17–18 Jan. 1990, London, UK, Elsevier, London, pp. 242–264.

[17] Quintiere, J. G., "Furniture Flammability: An Investigation of the California Technical Bulletin 133 Test. Part 1. Measuring the Hazards of Furniture," NISTIR 90-4360, National Institute of Standards Technology, Gaithersburg, MD, 1990.

[18] Parker, W. J., Tu, K.-M., Nurbakhsh, S., and Damant, G. H., "Furniture Flammability: An Investigation of the California Technical Bulletin 133 Test. Part III: Full Scale Chair Burns," NISTIR 90-4375, National Institute of Standards and Technology, Gaithersburg, MD, 1990.

[19] Ohlemiller, T. J. and Villa, K., "Furniture Flammability: An Investigation of the California Technical Bulletin 133 Test. Part II: Characterization of the Ignition Source and a Comparable Gas Burner," NISTIR 90-4348, National Institute of Standards and Technology, Gaithersburg, MD, 1990.

[20] Babrauskas, V. and Peacock, R. D., "Heat Release Rate: The Single Most Important Variable in Fire Hazard," *Fire Safety Journal*, Vol. 18, 1992, pp. 255–272.

[21] Fesman, G. and Jacobs, B. A., "Regulatory Flammability Testing for Public Assembly Furniture," Fire Retardant Chemicals Association 1990 Spring Meeting. "International Conference on Fire Safety: Fire Retardant Technology and Marketing," New Orleans, LA, 25–28 March 1990, pp. 213–225.

[22] NFPA 101, Life Safety Code 1991, National Fire Protection Association, Quincy, MA, 1991.

[23] Hirschler, M. M. and Shakir, S., "Comparison of the Fire Performance of Various Upholstered Furniture Composite Combinations (Fabric/Foam) in Two Rate of Heat Release Calorimeters: Cone and Ohio State University Instruments," *Journal of Fire Sciences*, Vol. 9, 1991, 222–248.

[24] Parrish, D. and Gallagher, J., "SPI Program on OSU RHR Testing of Fabric Foam Combinations," Sixteenth International Conference on Fire Safety, C. J. Hilado, Ed., Product Safety Corp., San Francisco, CA, 1991.

[25] Hirschler, M. M., "The Measurement of Smoke in Rate of Heat Release Equipment in a Manner Related to Fire Hazard," *Fire Safety Journal*, Vol. 17, 1991, pp. 239–258.

[26] Hirschler, M. M., "Heat Release from Plastic Materials," Chapter 12a, *Heat Release in Fires*, Elsevier, London, UK, V. Babrauskas and S. J. Grayson, Eds., 1992, pp. 375–422.

[27] "Standard for the Flammability of Mattresses and Mattress Pads," FF 4-72, amended, 16 CFR Part 1632, Code of Federal Regulations, Commercial Practices, Subchapter D: Flammable Fabrics Act Regulations, Vol. 16, part 1602–1632, 1 Jan. 1990, pp. 591–610.

[28] "Flammability Test Procedure for Mattresses for Use in High Risk Occupancies," CA TB 121, State of California, Bureau of Home Furnishings and Thermal Insulation, 3485 Orange Grove Avenue, North Highlands, CA, 95660-5595, Technical Bulletin 121, April 1980.

[29] "Flammability Test Procedure for Mattresses for Use in Public Buildings," CA TB 129, State of California, Bureau of Home Furnishings and Thermal Insulation, 3485 Orange Grove Avenue, North Highlands, CA, 95660-5595, Technical Bulletin 129, May 1992.

[30] Babrauskas, V., "Bench-Scale Predictions of Mattress and Upholstered Furniture Chair Fires—Similarities and Differences," NISTIR 93-5152, National Institute of Standards and Technology, Gaithersburg, MD, 1993.

[31] Emmons, H. W., *Journal of Heat Transfer*, Vol. 95, 1973, p. 145.

[32] Fisher, F. L., McCracken, W., and Williamson, R. B., "Room Fire Experiments of Textile Wall Coverings: A Final Report of All Materials Tested Between March 1985 and January 1986," Final Report to American Textile Manufacturers' Institute, ES-7583, University of California Berkeley Service to Industry, Report No. 86-2, March 1986.

[33] Belles, D. W., Fisher, F. L., and Williamson, R. B., "How Well Does the ASTM E 84 Predict Fire Performance of Textile Wallcoverings?" *Fire Journal*, Vol. 82, No. 1, 1988, pp. 24–30, 74.

[34] Fisher, F. L., Mowrer, F. W., and Williamson, R. B., "A Room Fire Screening Test Procedure," *Fire Technology*, Nov. 1983, pp. 238–250.

[35] "Standard Test Method for Evaluating Room Fire Growth Contribution of Textile Wall Covering," UBC 42-2, Uniform Building Code Standard No. 42-2-1991, International Conference of Building Officials, Whittier, CA, 1991, pp. 1387–1404.

[36] "Room Fire Test Standard for Interior of Foam Plastic Systems," UBC 17-5, International Conference of Building Officials, Whittier, CA, 1985, pp. 20–23.

[37] "Room Fire Test in Full Scale for Surface Products," ISO 9705, International Organization for Standardization, Geneva, Switzerland, 1990.

[38] Harkleroad, M. F., "Fire Properties Database for Textile Wall Coverings," NISTIR 89-4065, National Institute of Standards and Technology, Gaithersburg, MD, April 1989.

[39] Wickstrom, U., (Program Manager) Proceedings of the International EUREFIC Seminar 1991, 11–12 Sept. 1991, Copenhagen, Denmark, Interscience Communication, London, UK, 1991.

[40] "Method of Assessing the Ignitability and Fire Propagation of Building Materials When Subjected to Thermal Irradiance, (Epiradiateur)," NF P92-501, AFNOR, France

[41] "Fire Behaviour of Building Materials and Building Products (Brandschacht)," DIN 4102, Part 1, 1981, Germany

[42] "Method of Measuring the Surface Spread of Flame," BS 476, Part 7, British Standards Institution, Hampden House, 61 Green Street, London, W1, 1971

[43] Hirschler, M. M., "Why Not Use the Cone Calorimeter with Vertical Samples?," Business Communications Company, Fourth Conference on Recent Advances in Flame Retardancy of Polymeric Materials, 18–20 May 1993, Stamford, CT, M. Lewin, Ed., Norwalk, CT, 1993.

[44] "Standard for the Surface Flammability of Carpets and Rugs" (FF 1-70), 16 CFR Part 1630, Code of Federal Regulations, Commercial Practices. Subchapter D Flammable Fabrics Act Regulations, Vol. 16, part 1602–1632, 1 Jan. 1990, pp. 573–582.

[45] "Standard for the Surface Flammability of Small Carpets and Rugs" (FF 2-70), 16 CFR Part 1631, Code of Federal Regulations, Commercial Practices, Subchapter D: Flammable Fabrics Act Regulations, Vol. 16, part 1602–1632, 1 Jan. 1990, pp. 582–591

[46] Sears, A. B., "Nursing Home Fire: Marietta, Ohio," *NFPA Fire Journal*, Vol. 64, No. 3, May 1970, pp. 5–9.

[47] Watrous, L. D., "Two Fatal Hotel Fires," *NFPA Fire Journal*, Vol. 65, No. 1, Jan. 1971, p. 33

[48] Watrous, L. D., "28 Die in Pioneer Hotel, Tucson, Arizona," *NFPA Fire Journal*, Vol. 65, No 3, May 1971, pp. 21–27.

[49] Quintiere, J. G. and Huggett, C., "An Evaluation of Flame Spread Test Methods for Floor Covering Materials," NBS Special Publication 411, *Proceedings*, Symposium held at NBS, Gaithersburg, MD, 22 Aug. 1973, M. J. Butler and J. A. Slater, Eds., Nov. 1974, pp. 59–104.

[50] Fung, F. C. W., Suchomel, M. R., and Oglesby, P. L., "The NBS Program on Corridor Fires," *NFPA Fire Journal*, May 1973, pp. 41–8.

[51] Huggett, C., "Carpet Flammability and the NBS Corridor Fire Program," ASTM Standardization News, Vol. 1, No. 5, pp. 16–20.

[52] Tu, K.-M. and Davis, S., "Flame Spread of Carpet Systems Involved in Room Fires," NBSIR 76-1013, National Bureau of Standards, Gaithersburg, MD, June 1976.

[53] Denyes, W. and Quintiere, J. G., "Experimental and Analytical Studies of Floor Covering Flammability with a Model Corridor," NBSIR 73-197, National Bureau of Standards, Gaithersburg, MD, May 1973.

[54] Benjamin, I. A. and Adams, H. C., "The Flooring Radiant Panel Test and Proposed Criteria," *NFPA Fire Journal*, March 1976, pp. 63–71

[55] Adams, H. C. and Benjamin, I. A., "Development of the Flooring Radiant Panel Test as a Standard Test Method," NBSIR 79-954, National Bureau of Standards, Gaithersburg, MD, March 1980.

[56] "Fire Behaviour of Building Materials and Building Products," DIN 4102, Part 14, DIN, Germany, 1990.

[57] "Floor Coverings: Determination of the Burning Behaviour Using a Radiant Heat Energy Source," CEN/TC 127 ad hoc 3 N 25, Committee Europeen de Normalisation, 1989.

[58] Grand, A. F., Kaplan, H. L., Beitel, J. J., Switzer, W. G., and Hartzell, G. E., "An Evaluation of Toxic Hazards from Full Scale Furnished Room Fire Studies," *Fire Safety: Science and Engineering, ASTM STP 882*, T. Z. Harmathy, Ed., American Society for Testing and Materials, Philadelphia, 1985, pp. 330–353.

[59] Miller, A., "The US Home Product Report 1983–87, Forms and Types of Materials First Ignited in Fires," April 1991, National Fire Protection Association, Quincy, MA.

[60] Tomann, J., "Comparison of Nordtest Fire 007, CEN Draft Proposal (Radiant Panel) and Cone Calorimeter in the Fire Testing of Floor Coverings," *Proceedings*, Seventeenth International Conference on Fire Safety, Product Safety Corp., San Francisco, CA, C. J. Hilado, Ed., 13–17 Jan. 1992, pp. 26–37

[61] Hirschler, M. M., "Smoke and Heat Release and Ignitability as Measures of Fire Hazard from Burning of Carpet Tiles," *Fire Safety Journal*, Vol. 18, 1992, pp. 305–324.

[62] Hirschler, M. M., "Carpet Tiles and Fire Performance," *Crosstalk*, Vol. 40, No. 7, April 1992, pp. 1–4.

[63] Briggs, P. J., Harris, S. R., Ollerenshaw, M., Van Hees, P., and Van Wesemael, E., "Full-Scale Fire Testing of Carpets in Room/Corridor Scenarios and Comparisons with Small-Scale Test Procedures," *Flame Retardants '92*, Plastics & Rubber Institute, Elsevier, London, 1992, pp. 297–307.

[64] Vandevelde, P. and Van Hees, P., "Full-Scale Fire Tests on PVC Floor Coverings in a Room Corridor Rig and Comparison with Small Scale Tests," *PVC '93, The Future*, Institute of Materials, Brighton, UK, 1993, pp. 443–453.

[65] Hirschler, M. M., "How to Measure Smoke Obscuration in a Manner Relevant to Fire Hazard Assessment: Use of Heat Release Calorimetry Test Equipment," *Journal of Fire Sciences*, Vol. 9, 1991, pp. 183–222.

[66] Hirschler, M. M., "The Measurement of Smoke in Rate of Heat Release Equipment in a Manner Related to Fire Hazard," *Fire Safety Journal*, Vol. 17, 1991, pp. 239–258.

[67] Belles, D. W. and Beitel, J. J., "Do Multi-Layer Draperies Pass the Single-Layer Fire Tests?," *Fire Journal*, Vol. 82, No. 5, 1987, pp. 25–30, 91.

[68] Davis, S. and Villa, K. M., "Development of a Multiple Layer Test Procedure for Inclusion in NFPA 701: Initial Experiments," NISTIR 89-4138, National Institute of Standards and Technology, Gaithersburg, MD, Aug. 1989.

[69] Standard for the Flammability of Clothing Textiles, 16 CFR Part 1610, Code of Federal Regulations, Commercial Practices, Subchapter D: Flammable Fabrics Act Regulations, Vol. 16, part 1602–1632, 1 Jan. 1990, pp. 487–504.

[70] Needles, H. L., "Current Issues in Clothing Flammability: Testing and Regulation," Sixteenth International Conference on Fire Safety, C. J. Hilado, Ed., Product Safety Corp., San Francisco, CA, 1991, pp. 175–177.

[71] Abraham, C. J., "FR Technology and Standards for Wearing Apparel—A Time for Upgrading," Second BCC Conference on Flame Retardancy of Polymeric Materials, 14–16 May 1991, Stamford, CT, M. Lewin, Ed., Business Communications Co., Norwalk, CT, 1991.

[72] Krasny, J. F., "Flammability Evaluation Methods for Textiles," *Flame-Retardant Polymeric Materials*, Vol. 3, M. Lewin, S. M. Atlas, and E. M. Pearce, Eds., Plenum Publications, New York, 1982, pp. 155–200.

[73] "Standard for the Flammability of Children's Sleepwear: Sizes 0 Through 6X," 16 CFR Part 1615, FF 3-71 Code of Federal Regulations, Commercial Practices, Subchapter D: Flammable Fabrics Act Regulations, Vol. 16, part 1602–1632, 1 Jan. 1990, pp. 515–544.

[74] "Standard for the Flammability of Children's Sleepwear: Sizes 7 through 14," 16 CFR Part 1616, FF 5-74 Code of Federal Regulations, Commercial Practices, Subchapter D: Flammable Fabrics Act Regulations, Vol. 16, part 1602–1632, 1 Jan. 1990, pp. 544–573.

[75] "Standard for Office Furnishings," 2nd Edition, July 1990, UL 1286, Underwriters' Laboratories, 333 Pfingsten Rd., Northbrook, IL, 60062, 1990.

[76] Hirschler, M. M., "Concepts Behind ASTM E 931-85: Empirical Practice for Classification of Occupancies for Their Relative Fire Hazard to Life," this publication, pp. 32–49.

ATTACHMENT 13