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The Influence of Ignition Source on the Flaming Fire Hazard of Upholstered Furniture

Thomas G. Cleary, Thomas J. Ohlemiller & Kay Villa*

Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

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ABSTRACT

A set of upholstered chairs constructed from five different fabric/foam combinations was subjected to a variety of ignition sources suggested by fire statistics. The sources included a cigarette, a small match-like flame, an incandescent lamp, a space heater, and a large flame source (TB 133 ignition source). The tests were performed in a furniture calorimeter where heat release rate and species production rates were obtained. For any chair type, the time to the peak heat release rate depended on the ignition sequence, but the magnitude of the peak did not, within the scatter of the data for any given chair. HAZARD I, the fire hazard assessment method developed at the National Institute of Standards and Technology (NIST), was used to quantify the hazard posed by the different ignition scenarios. Not one of the ignition scenarios examined consistently yielded the greatest potential hazard for all chair types tested when ignition and sustained burning were achieved. No deaths were predicted when a working smoke detector was present. When a detector was not present, the results from the limited number of scenarios considered confirm the importance of a low peak heat release rate and to some extent a slow rate of rise to lessen the hazard of upholstered furniture fires.

INTRODUCTION

In the USA, upholstered furniture fires are the single leading cause of residential fire deaths, accounting for 23% of such deaths in the period 1983–87.[1] Smoking materials, principally cigarettes, are implicated in

* Present address: American Textile Manufactures Institute, Washington, DC.

the majority of these fires, about 53%. The cigarette ignition resistance of upholstery materials is the focus of two voluntary national standards, NFPA 260 and 261;[2] the former is similar to a standard adopted by the Upholstered Furniture Action Council in the late 1970s. There are no similar national standards for flaming ignition resistance of residential furniture nor for the flaming behavior that can result from smoldering or flaming ignition. The study summarized here is focused primarily on heat sources which cause the flaming ignition of upholstered furniture, rather than on cigarettes which initiate smouldering combustion, and on the resulting rate of heat release behavior.

The flaming ignition sources involved in upholstered furniture fires cover a considerable spectrum but their characteristics are not always well-defined. For example, 'incendiary or suspicious' ignition sources comprised nearly 15% of residential upholstered furniture fires in 1983–87.[1] This suggests strong, arson-like sources; these sources are not further specified in this reference. Children playing with matches, cigarette lighters or candles resulted in 10% of such fires in this time period. Such sources are relatively well-defined and, to some extent, characterized with respect to duration and heat flux,[3] but this last category is the exception. The mix of remaining ignition sources is suggested by studies done by the Consumer Product Safety Commission on fire statistics from the 1970s:[14] space heaters, electric blankets/pads, extension cords, electric lamps, etc. Each of these types of sources obviously can vary substantially depending on the particular circumstances. Further lacking from essentially all of these potential ignition sources is information on where they typically come into contact with a furniture item.

In the present study, the goal is to obtain some assessment of the extent to which the fire hazard of an upholstered furniture item depends on how it is ignited. (Whether or not ignition occurs is also a very relevant part of the hazard assessment since it may not happen with some of the weaker sources, but this is not addressed here.) This issue was previously examined to a very limited extent using two small ignition sources on furniture mock-ups.[5] Given the variability of ignition sources, it is quite conceivable that the time for a fire to develop to its peak level in an item of furniture might depend on where and how it is ignited. The measure of the fire 'level' referred to here is the time-dependent heat release rate from the furniture fire; it is this characteristic of a fire which is believed to best characterize the potential hazard the fire would usually present in the context of a residential structure.[6–8] If the heat release rate versus time is appreciably sensitive to the details of the ignition process, this would complicate the assessment of the hazard implicit in a given design of upholstered furniture. This assessment is already made quite complex by the known sensitivity to the exact material combinations used in chair construction, especially the fabric and cushioning materials.[7]

In order to pursue the above goal with finite resources, it has been necessary to make careful choices regarding ignition sources and upholstery materials. Five ignition sources, suggested by the above discussion, were chosen and applied in duplicate tests, to five fabric/padding combinations. An effort was made to choose from across the spectrum of typical residential fabric/padding combinations but no statistical basis can be provided for the particular combinations chosen. The chair geometry and underlying structural materials were fixed.

Each source was applied at only one locale on the chair. Each location was chosen to be plausible, given the nature of the source. A related study of the effect of varied ignition location for a single ignition source is reported in Ref. 5.

The heat release behavior was obtained using the NIST Furniture Calorimeter. HAZARD I, a fire assessment methodology developed at NIST over the past several years[9] was used to estimate the effects on life safety of the fire location, the time of day, the age and health of the occupants, the presence of smoke detectors, etc. The limited number of fire scenarios which could be examined here was chosen using the extensive effort to reproduce U.S. furniture fire statistics, developed by the National Fire Protection Research Foundation.[10–12]

EXPERIMENTAL DETAILS

Test apparatus

The tests were all performed in the NIST Furniture Calorimeter.[13] This consists of a large overhead hood which captures the combustion products from the burning chair. The oxygen level and flow rate of the exhaust gases are monitored continuously during a burn. From this information one can infer the amount of oxygen being used in the burning process per unit time. The amount of heat evolved per mass of oxygen consumed is nearly constant for most organic materials so that one can thus infer the rate of heat release.[14] The chair rests on a load cell so that its mass can be recorded during a burn. The exhaust gases are also monitored for CO and CO_2. The calorimeter was calibrated using a 0·91 m diameter burner which consumed natural gas. Calibration fires up to 750 kW were used.

Upholstered chairs

All of the chairs had the same geometric configuration; Fig. 1 shows the shape and the dimensions. This is the same chair geometry used in our previous studies of California Technical Bulletin TB 133.[13,15] The chairs were custom manufactured for this study by Shelby-Williams Inc.; the basic chair model is their lounge chair, style No. 495 (specific brand names are mentioned for clarity only and do not imply any endorsement by the National Institute of Standards and Technology).

The chair frame was composed of a mixture of hardwood structural elements and plywood panels, with the latter utilized in such places as the tops of the chair arms and the front panel below the seat cushion. The seat was supported by a platform spring of steel wire.

The fabrics are described in Table 1 which also gives the letters by which all of the chairs are referred to in this paper. The polyurethane, present in all of the chairs, was a conventional nonretarded material with a nominal density of 24 kg/m^3 (1·5 lb/ft^3). Note that only chair type B incorporated a wrap of polyester batting around the foam

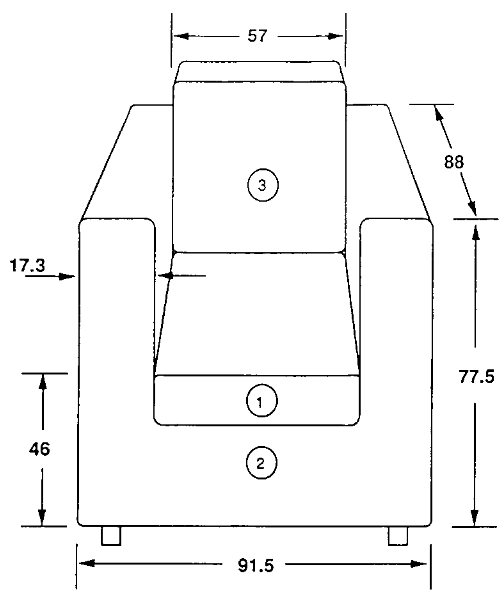

Fig. 1. Style of chair tested, all dimensions in centimeters. Circled numbers are the positions of surface temperature measurements from radiant space heater exposure (Table 3).

TABLE 1
Characteristics of Fabrics and Cushioning Materials

Chair designation	*Description*
A	340–410 g/m^2 (10–12 oz/yd^2) cotton fabric (no backcoating); non-fire-retarded cotton batting overwrap on polyurethane cushions[a] and on interior of side arms
B	63% nylon/26% olefin/11% acrylic fabric with latex backcoating; non-fire-retarded polyester batting overwrap on polyurethane cushions
C	100% olefin fabric with latex backcoating; no overwrap on polyurethane cushions
D	Acrylic facing on rayon/cotton backing fabric; no overwrap on polyurethane cushions
E	Expanded vinyl fabric; no overwrap on polyurethane cushions

[a] All of the polyurethane foam was conventional non-fire-retarded material with a density of 24 kg/m^3 (1·5 lb/ft^3).

cushions; this was avoided in the others, despite its current market popularity, in order to simplify the number of interacting materials. Chair type A did have a comparable wrap of cotton batting around the foam cushions and along the inner surface of the chair arms. This wrap, in combination with the rather light weight cotton fabric, rendered this chair type uniquely ignitable by a smoldering cigarette. (The cotton batting was nominally non-fire retarded but there were some indications—a weakly greenish flame—of a slight boric acid presence during the experiments.)

Reference 11 gives some rough estimates of the range of upholstered furniture fabric and padding materials currently in use in the USA. The results there indicate that 57% of the currently-used furniture has the kind of materials that would make it potentially susceptible to smoldering ignition by cigarettes; this includes furniture having a cellulosic cover fabric over cotton, latex or polyurethane materials. The remaining 43% has a thermoplastic fabric over a polyester batting and polyurethane foam, providing an inherent cigarette ignition resistance. Inspection of Table 1 indicates that we have included one type of chair representative of the biggest fraction of current usage (chair type A). The others are examples of the diverse spectrum of the current market. A more detailed breakdown of that market is not available.

Ignition sources

The five ignition sources used in this study were chosen to approximate the spectrum of sources indicated by US fire statistics. These statistics do not provide specific information on materials and circumstances of usage which are most likely to result in furniture ignition. Therefore, we have tended toward choices which should accentuate the severity of the effects of the particular source. The spatial heat flux patterns of the ignition sources used here are summarized in Ref. 16.

For an arson-like source, the TB 133 ignition source was used.[15] The burner simulates the impact of burning five crumpled sheets of newspaper piled up on the chair seat. Its use here followed the TB 133 procedure which calls for an 80-s exposure with direct flame impingement on the chair seat and seat back, however, the gas flow rate was 11 liters/min not the 13 liters/min now required in the TB 133 standard. This source leads to rapid involvement of the whole chair.

The feature of radiant heat sources such as room heaters and lamps which can potentially increase the severity of a fire is their tendency to preheat a significant portion of the upholstered furniture item. Such preheating will tend to accelerate flame spread over the surface where it has occurred. The two sources used here (space heater and incandescent lamp) provided such preheating.

The radiant heater contained two 38 cm long vertical quartz tubes backed with a metallic reflector; the heater is rated at 1500 W. To increase the severity of the preheating, the heater was placed 10 cm (distance from the front guard grill to the front edge of the seat cushion) in front of the chair, centered on the left/right plane of symmetry of the chair. The preheating was thus most intense on the front edge of the seat cushion and the front panel of the chair but it extended to all surfaces visible in Fig. 1. This exposure caused only a weak, localized pyrolysis of the chair materials in a 30-min preheat time. At the end of this interval, the heater was tipped forward so that the front guard touched the front top edge of the seat cushion; pyrolysis of the fabric/foam materials was greatly accelerated so that an ignitable mixture of fuel gases was available typically in about 1 min after tip over. The ignitability of the gases was tested at 10-s intervals with an electric spark (see Note 1). Sustained flaming typically followed immediately and the heater was removed to prevent its destruction in the subsequent fire.

The electric light source was utilized in an analogous manner, though in a location more suited to its role as a reading lamp. It should be noted that the light bulb used here was rather unique in that it was a focused quartz-halogen lamp (55 W) with a more intense local heat flux than would be expected from most reading lights; in this sense it provides a worst case situation. The light (enclosed in a typical hooded desk lamp fixture) was placed near a rear corner of the chair and was allowed to preheat an area centered around the rear top of one chair arm and the side of the back seat cushion. The preheating lasted for 30 min, as above, but the incident heat fluxes were much lower than with the radiant heater, because the closest distance from lamp to chair was about 35 cm. At the end of the preheat interval, the lamp was tipped onto the top of the chair arm. As a result the front of the bulb ended up about 5 cm from the top of the chair arm at a point about 33 cm from the rear end of the arm. The focused radiation from the lamp then quickly acted to cause a localized area of pyrolysis and an ignitable mixture of gases was present after about 1–2 min with certain chairs, as determined by application of the electric spark igniter in the same manner as above. The chair types which produced flaming ignition in this manner were A and D though the flames died in less than 1 min on chair type A. The other chairs did not yield flaming ignition as a consequence of this sequence (see Note 2).

The match-like flaming ignition source was adapted from British Standard 5852, Part 1. For convenience, propane was used instead of butane; this should have little impact on the heat fluxes imposed.[3] The source consists of a stainless steel tube (8 mm OD, 6·5 mm ID) from which propane flows at a metered rate of 45 cm^3/s; this produces a flame shown to be representative of a variety of matches found in the UK. After a 2-min free burn to warm the tube, the source is placed in the top of the crevice formed by the seat cushion and the inner side arm; the flame location is approximately midway (front/back) along the crevice. The flame impinges on both the edge of the seat cushion and the side arm. After 20 s it is removed carefully so as not to extinguish what is typically a quite fragile flame on the upholstery surfaces.

The cigarette used was a 85 mm, non-filter Pall Mall. It was lit and given 2 min to approach a steady state before being placed similarly to the match source above. It was not removed unless it had burned its full length with no ignition of the chair.

Throughout this paper we use a short-hand notation for the ignition sources as follows:

B: TB 133 ignition source,
H: radiant space heater,
M: match-like source,
L: lamp,
C: cigarette.

EXPERIMENTAL RESULTS

General observations

Of the 25 combinations of chair types and ignition sources which were tested, 15 ignited and burned. Replicate tests of each produced the same ignition behavior. Table 2 shows the ignition and sustained burning propensity for each chair type/ignition source combination.

For the following discussion we focus on the magnitude and time of the peak rate of heat release, since those represent the most significant hazard for typical furniture items. The detailed results for each chair that ignited and burned are given in Ref. 16. Heat release rate, mass loss rate, CO, CO_2 yield, and 'smoke' yield (specific extinction area from light extinction measurements) are shown there. These data are the required time-varying values used as inputs into HAZARD I (though the actual input data are in a different form).

Observations of ignition and early development

The TB 133 ignition source is by far the most severe of all the ignition sources in terms of heat flux exposure and area directly ignited. This source promotes left/right symmetrical burning of a chair due to its location. The 80-s duration of this source was sufficient to ignite the side arms, seat cushion and seat back cushion of these chairs. The heat release rate from the ignition source is approximately 16 kW for the 80-s duration.

TABLE 2
Ignition and Sustained Burning Propensity

Chair	*Ignition source*				
	B (*TB* 133)	*H* (*Radiant heater*)	*M* (*Match*)	*L* (*Lamp*)	*C* (*Cigarette*)
A	√[a]	√			√
B	√	√	√		
C	√	√	√		
D	√	√	√	√	
E	√	√			

[a] Denotes ignition and sustained burning.

TABLE 3
Typical Surface Temperatures (°C) from Radiant Space Heater Exposure (at 20 min)

Chair type	*Position 1*	*Position 2*	*Position 3*
A	157	81	44
B	171	80	34
C	164	93	37
D	204	80	47
E	147	91	51

The radiant space heater is positioned such that the (vertical) front portion of the seat cushion is preheated and then ignited. Surface temperatures at various positions were recorded with a thermocouple probe (inserted briefly to record temperature, then removed) for each chair after approximately 20 min of preheating; temperatures after the full 30 min of preheat are expected to be slightly higher. The surface temperatures for three positions (see Fig. 1 for the approximate locations), the front (vertical) center of the seat cushion (position 1, the closest distance to the source), the center of the front of the chair below the seat cushion (position 2), and the center of the seat back cushion (position 3) were recorded at 20 min, as shown in Table 3.

The temperature differences among chair types result from differing fabric weights and differing radiation absorptivities. The rate of flame spread on thick materials is expected to vary inversely as the square of the difference between the ignition temperature of the material and its initial temperature, assuming the heat feedback from the flames does not vary.[17] Given this and an estimate of 375 °C as an ignition temperature, the position 1 temperatures would effect a considerable increase in flame spread rates (200–300%) and position 2 temperatures an increase of only about 30%. Thus, the above temperature information (supplemented by the heat flux distribution information in Ref. 16), implies that the acceleratory effect of the preheating is largely localized to the front of the chair, closest to the heater as is logical.

For each of the chairs, after ignition by the radiant heater exposure/electric spark, the flames travel upward on the front lip of the seat cushion and then across its horizontal surface, slowly at first. When the flames reach the chair arms, more upward spread is possible, which accelerates the heat release rate of the chair. For the repeat test of chair A, the initial flames went out. This chair was allowed to smolder for an additional 3600 s then was ignited by the electric spark. This smoldering period did not appreciably affect the magnitude of the peak heat release rate, but it did affect the shape of the heat release rate curve in that a faster rise in heat release rate was observed. Chair types B and C both exhibit double peaks in the heat release rate curve that results from this ignition source for reasons which were not evident.

The match-like source ignited and yielded sustained flaming for three of the five chair types. Chair type C was subjected to this ignition source a total of seven times, and only yielded sustained flaming in two of those attempts. Sustained flaming with this source and chair type C appeared to be a random event which depended on how the fabric opened up initially as it melted and whether the flames could anchor to the exposed foam before the flaming fabric extinguished. Here we only distinguish between chairs that ignited and those that did not ignite and do not include an ignition probability factor in any of the analyses which follow.

The lamp exposure/electric spark ignited and yielded sustained burning of only one of the chair types (D). The maximum surface temperature after approximately 20 min of preheating of chair type D (but prior to tipping the lamp over) by the lamp was 37 °C. The horizontal top portion of the chair arm was ignited approximately 8 cm from the seat back cushion. The initial burning area grew from a few centimeters in diameter outward in a circular pattern until it reached the sides of the arm and the seat back cushion. This initial spread was a relatively slow process and was reflected in the very slow initial rise in the rate of heat release curve. After the flames spread to the seat back cushion, the heat release rate picked up substantially.

The cigarette source was the only source that yielded smoldering ignition initially. Only chair type A smoldered as a result of this exposure. A spontaneous transition from smoldering to flaming occurred with both chairs after approximately 3 h. Prior to the transition to flaming, nearly 100% of the seat cushion was smoldering, as indicated by the light-to-dark brown color of the fabric. The smoldering had elevated the temperature of a large portion of the chair. This preheating effect was reflected in the shape of the heat release rate curve where the time of the peak was less and the magnitude of the peak was somewhat higher than with other sources, in spite of there having been some fuel loss due to the smoldering process.

Peak heat release rate

The main differences in heat release behavior among the sources are in the time from initial flaming (ignition) (see Note 3) to the peak heat release rate and in the magnitude of the peak. Figures 2–6 capture

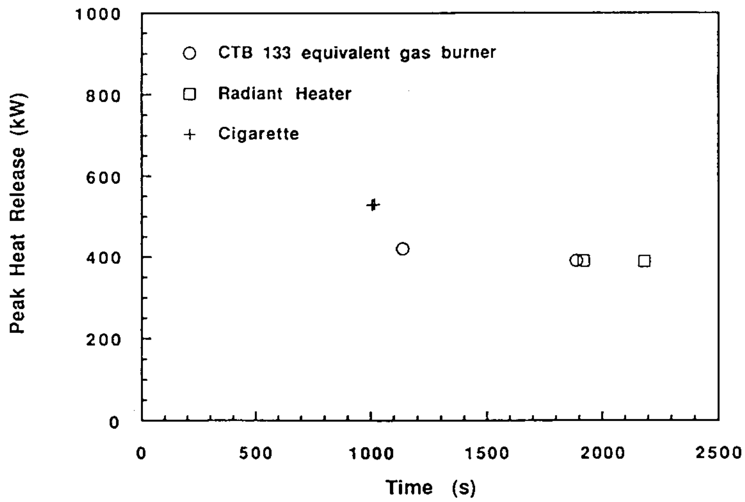

Fig. 2. Time of peak heat release rate for various ignition scenarios applied to chair type A. Time = 0 at beginning of flaming.

these features of the heat release rate curves by showing only the magnitude of the peak heat release rate (after the data were smoothed with a running three-point average) and the time from initial flaming to the peak for each chair, for each source that yielded sustained burning of that chair. In most cases, the time from first visible flaming to the time of peak heat release rate was shortest with the TB 133 ignition

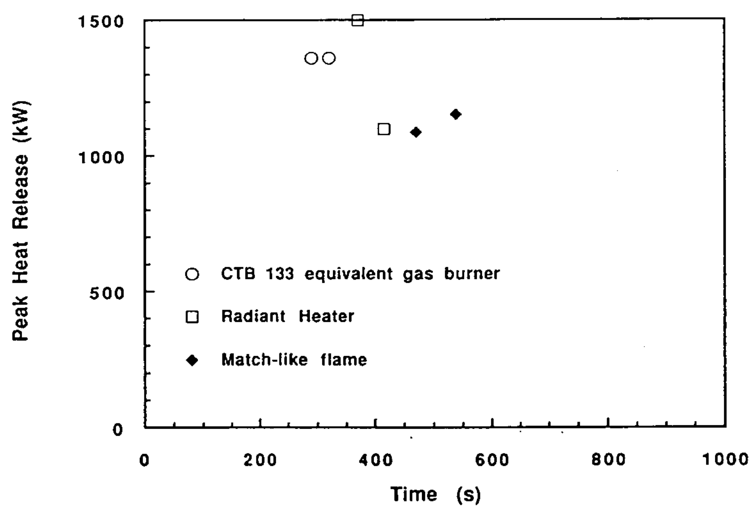

Fig. 3. Time of peak heat release rate for various ignition scenarios applied to chair type B. Time = 0 at beginning of flaming.

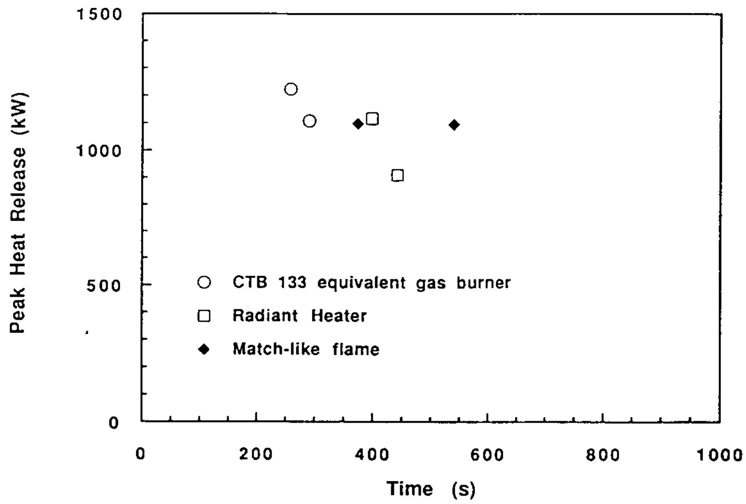

Fig. 4. Time of peak heat release rate for various ignition scenarios applied to chair type C. Time = 0 at beginning of flaming.

source. The cigarette ignitions of chair type A were an exception; the cigarette source consistently yielded an earlier flaming peak than did the other sources, presumably because of the extensive preheating in the smoldering phase. A repeat of the space heater/spark test with chair D was also an exception. The next fastest peak after the TB 133 ignition source was achieved with the radiant space heater for most

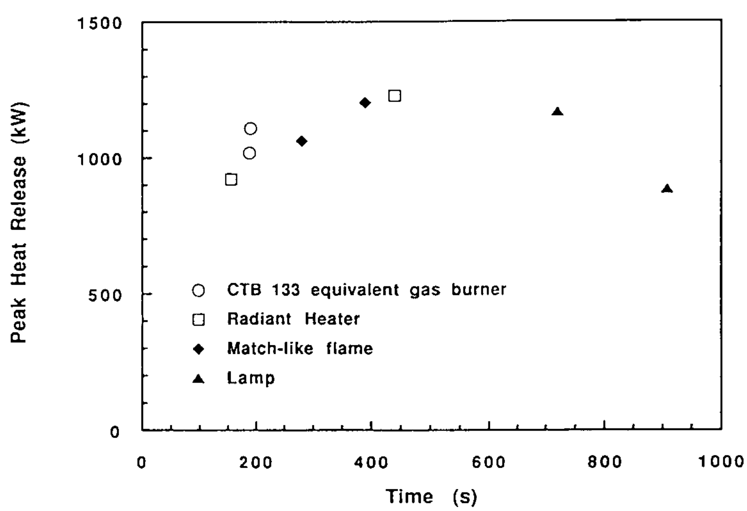

Fig. 5. Time of peak heat release rate for various ignition scenarios applied to chair type D. Time = 0 at beginning of flaming.

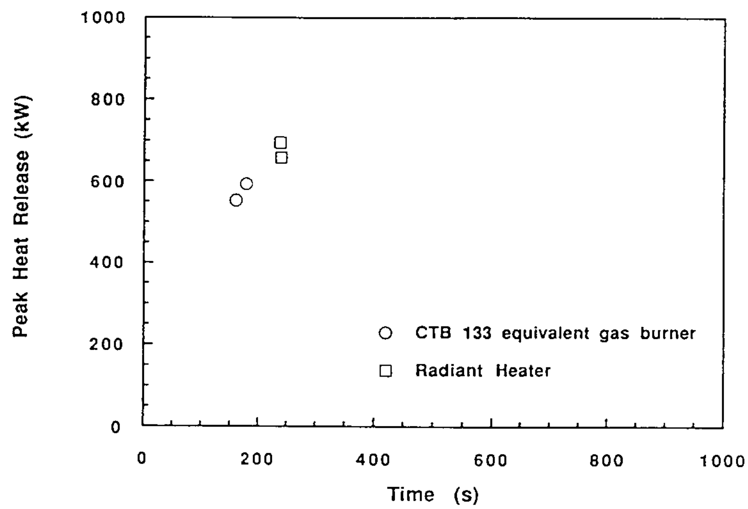

Fig. 6. Time of peak heat release rate for various ignition scenarios applied to chair type E. Time = 0 at beginning of flaming.

cases (the radiant space heater is third with chair type A and D), followed by the match-like source, then the lamp.

At the peak heat release rate, the exposed surfaces of the seat cushion and seat back cushion were usually fully involved in the burning for all chair types and ignition sources. At the peak, the chair arms were also involved and had either burned through to the exterior, or were close to doing so. Thus it is not surprising that the TB 133 ignition source, which ignites a substantial fraction of all these surfaces, tended to yield the earliest peak.

Inspection of Figs 2–6 shows that, for each chair type, the magnitudes of the peak heat release rates are similar regardless of ignition source, and, given the noise level in the peak heights, no definite trend in the peak heat release rate is observed for any particular ignition source, across the spectrum of chair types, with the exception being cigarette ignition of chair type A. In this last case, it does appear that the preheating during the very extended smoldering phase does facilitate more rapid flame spread over the chair surfaces yielding a higher mass loss rate and rate of heat release. The effect is not very strong, however.

We can summarize the main points that emerge from examination of the experimental data as follows:

1. Some of the weak ignition sources do not have sufficient energy input to yield sustained, spreading flames for all of the chair types.
2. There can be substantial differences in the time to the peak heat release rate for different ignition sources.

3. The magnitudes of the peak heat release rates for the different ignition sources, given the same chair type, are close and appear to be within the scatter of the data. This and the previous conclusion confirm earlier inferences made from a very limited data set.[18]

In the related study of the effect of ignition location on heat release behavior,[5] the same ignition source, a 10 kW gas burner (not used in the present study), was applied to four locations on chairs having the same geometry (but different materials) as those used here. The locations were: (1) the center of the seat cushion, (2) lower center of the chair back, (3) lower center of the chair front, (4) the lower center of one side of the chair. It was found that the peak rate of heat release was independent of ignition location. However, the time at which the peak occurred could vary widely with the location of the ignition source. Generally, ignition of the seat cushion gave the quickest peak. This result suggests that most of the differences in the timing of the peak in the heat release curves with differing ignition sources seen in the present study are a consequence of the differing locations as well.

HAZARD I SIMULATIONS

In order to quantify the impact of the differences between ignition sources on hazard development within a residential context, we use the HAZARD I fire hazard assessment methodology. Below we describe our approach and some results from HAZARD I.

HAZARD I is a prototype fire hazard assessment methodology that can predict, to a reasonable extent, the outcome of a building fire scenario in terms of the survivability of the occupants.[9] The computer models in HAZARD I include a fire and smoke transport model, a human response-to-fire model, and a model that predicts the deaths of the occupants based on their exposure to the environmental hazards of the fire. The PC-based software is limited to a total of six individual rooms including the fire room. The user specifies the room sizes and layout. The fire, in the form of a heat release rate curve, is a prescribed input to the model. The fire and smoke transport model is a so-called zone model where each room is split into upper and lower layers. Transport of the smoke and hot gases into and out of individual rooms is calculated. The temperatures, chemical species concentrations, and heat release rates of both the upper and lower layers are some of the variables calculated. The occupancy set is specified by the user. Each person must be specified according to their sex, age, position (i.e. room), whether they are awake or asleep, whether they are intoxicated, and whether they require assistance in order to flee the fire. For a given fire scenario, HAZARD I predicts whether or not the occupants will escape the building, survive in place, or die. The time to escape and the exit route or, alternatively, the time, location, and cause of death are provided for each occupant (see Note 4).

The National Fire Protection Research Foundation sponsored the development of a fire risk assessment method for new products that utilized HAZARD I as the fire outcome predictor.[10–12] That method was checked by its ability to reproduce the US national fire statistics for various specific fire scenarios. A successful case was upholstered furniture fires in residences. The outcome of the furniture fire study was employed here to guide certain parameter choices in the use of HAZARD I for quantifying the differences between ignition sources with respect to fire hazard.

Analysis procedure

A six-room, one-story ranch house was selected for the computations here since US census data, as quoted in Ref. 10, indicate that approximately 70% of single family homes are one-story. This is the same building configuration used in the NFPRF upholstered furniture study.[11] A floor plan for the ranch house is shown in Fig. 7. It was not

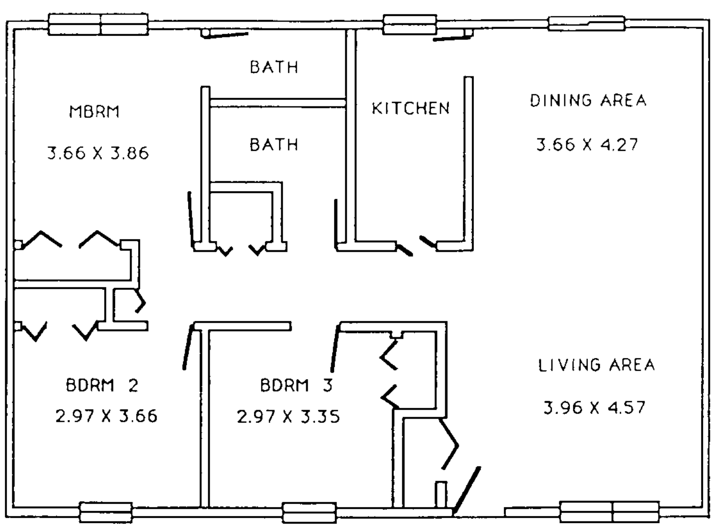

Fig. 7. Floor plan of house specified in HAZARD I simulations. Dimensions in meters.

possible to select a single most prevalent occupant set since, from census data as quoted in Ref. 11, the frequency of any one set is small (i.e. the distribution is broad). The occupant set selected consisted of a father, mother, infant, and grandmother. The infant and grandmother require assistance to move, and thus each must be rescued by either the father or mother. The scenario includes a night-time fire, therefore, all occupants were placed in bedrooms and assumed to be asleep (see Note 5). A daytime fire scenario would result in few or no casualties due to rapid detection of the fire and subsequently rapid escape.

HAZARD I simulations were run with and without a working smoke detector. Based on fire statistics quoted in Ref. 10, the probability that a working smoke detector is present in a house where a fire occurs is approximately 19%. In HAZARD I, it is assumed that smoke has an odor to it and can wake up sleeping occupants; the thicker the smoke, the stronger the stimulus to awake and alert occupants. Thus, that is the main mechanism by which the occupants are alerted to the fire if no properly functioning smoke detector is present. When a smoke detector is prescribed, HAZARD I determines the time of detector response.

HAZARD I was run with either the fire as being in the living room/dining room or in the master bedroom since most upholstered furniture fires occur in these spaces.[11] The measured data from each chair burn were input into HAZARD I to describe the fire (see Note 6). Out of 50 chairs tested, 30 ignited and yielded sustained flaming. Since two separate fire locations were specified, 60 simulations of the smoke and heat transport were run. In addition, the escape and tenability program were run twice (with and without a working smoke detector) for each of the fire simulations. It was assumed that once occupants reached a window they could escape after a 20 s delay. This was the delay time specified and used in the NFPRF project.[11]

Results

Table 4 shows the results for all of the simulations in terms of total deaths for each chair type/ignition source combination. The fatalities are predicted by the TENAB program which is part of HAZARD I, subsequent to the analysis of the smoke and heat transport and people movement. Note that the maximum possible number of deaths in any box of Table 4 combining a given chair type and ignition source is 32 (four occupants, two tests per chair type, two fire locations, and two detector options).

None of the chair fires was large enough by itself to cause flashover in the room of origin (assuming a flashover criterion of a 600 °C upper

TABLE 4
Number of Predicted Deaths from HAZARD I (see text)

Chair type	*Ignition source*					
	B	*H*	*M*	*L*	*C*	Σ
A	2	4	NI[a]	NI	0	6
B	4	6	6	NI	NI	16
C	4	0	1	NI	NI	5
D	6	6	4	5	NI	21
E	0	0	NI	NI	NI	0
Σ	16	16	11	5	0	48

[a] No ignition (i.e. no sustained flaming and thus no deaths).

layer temperature), and since we only consider the chair rate of heat release and not any secondarily ignited items, the concomitant increase in CO due to ventilation limitations as a fire approaches flashover[6,19] was not included here. This approach differs from that of the NFPRF project committee in that they supplemented their generic upholstered furniture heat release rate curve by adding a 't^2 fire' (see Note 7) to the heat release rate curve when the peak heat release rate for the chair was reached. This served to model secondarily ignited items in the room and essentially forced the fire to flashover if a sufficient oxygen supply rate was available.[10,11] In every case run here, the occupants either escaped the house or were either trapped or left behind (not rescued in the case of the infant or grandmother) prior to the observed peak heat release rate. Occupants remaining in the house always become fatalities. If the fire room were to reach flashover some time after the peak heat release rate of the chair is observed, the outcome would be unchanged. Therefore, the provision of secondarily ignited items behaving in accord with the NFPRF study is inconsequential for these simulations. This lack of dependence of the outcome on secondary item ignition simplifies the present analysis, but it cannot be said to be a general result.

The input fire uses data from an open-configuration furniture calorimeter. The computer simulation includes no heat feedback from hot walls or hot accumulated gases in the upper layer. However, in this case, the lack of thermal reinforcement does not result in a serious underestimation of the hazard for the following reasons:

1. Parker *et al.* observed that for upholstered chairs similar to the ones tested here, the heat release rate results from the furniture

calorimeter and room fire tests in the proposed ASTM room were nearly identical up to an output of approximately 600 kW.[13]

2. In the simulations, the outcome (escape or being trapped) was decided prior to the peak heat release rate (usually less than 600 kW but up to 850 kW). In the cases where the heat release rate of the fire was greater than 450 kW at the time of occupant alert, fatalities occurred.

Out of 120 simulations, 23 resulted in fatalities. No deaths were calculated in any case where a working smoke detector was prescribed. The alarm from the detector is assumed to wake the occupants and they had sufficient time to escape before they were exposed to fatal fire conditions or trapped by smoke. This result is independent of the severity of the ignition source examined here.

In approximately one third of the simulations where fatalities occurred, either the father or mother or both became trapped during an escape attempt, while in two thirds of the simulations the infant, grandmother or both were not rescued. Note that, in this sense, their fate was dictated by the smoke or heat conditions that led to entrapment or non-rescue. The subsequent cause of incapacitation was smoke toxicity (fractional effective dose of CO, CO_2 and O_2 based on Purser's analysis[20]) 78% of the time and the remainder on heat flux exposure. The fractional effective dose criterion is incomplete because of a lack of HCN concentration in the data sets. The cause of death is always from smoke toxicity (concentraton–time criterion). We did not consider exposure to 100 °C gases as immediately lethal, which is the default temperature criterion in HAZARD I. A temperature of 100 °C can be tolerated for many minutes according to Purser.[20] If we do consider the case where incapacitation occurs at 65 °C and death at 100 °C, the total number of deaths goes up to 90 with the temperature limit the cause of fatality in 86% of the cases.[16]

The concentration–time criterion specifies a constant smoke toxic potency. The default value in HAZARD I is 900 mg min/liter as the lethal dose. In the NFPRF study it was found that this toxic potency had to be increased by an order of magnitude in order for smoke inhalation to account for the majority of furniture fire deaths.[12] Here a value of 300 mg min/liter (a factor of three increase in potency) was assumed to be a lethal dose. This change from 900 to 300 mg-min/liter did not affect the cause of death but only hastened the time to death.

The hazard for a particular chair appears to be related to the peak heat release rate. A total of 40 simulations were run where the chair peak heat release rate was less than 800 kW. Fatalities were calculated calorimeter and room fire tests in the proposed ASTM room were nearly identical up to an output of approximately 600 kW.[13]

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TABLE 5
Number of Predicted Deaths from HAZARD I (Fire in Living Room/Dining Room)

Chair type	*Ignition source*					
	B	*H*	*M*	*L*	*C*	Σ
A	0	4	NI[a]	NI	0	4
B	2	6	4	NI	NI	12
C	4	0	1	NI	NI	5
D	2	4	4	4	NI	14
E	0	0	NI	NI	NI	0
Σ	8	14	9	4	0	35

[a] No ignition (i.e. no sustained flaming and thus no deaths).

in three of those cases. The remaining 80 simulations were run with chair peak heat release rates greater than 800 kW. Fatalities were calculated in 20 of those cases. Thus for these simulations, the peak heat release rate is a strong indication of the hazard.

From Table 4 it is observed that no single ignition source presents the greatest hazard for all chair types. For example, the TB 133 ignition source results in more deaths than the radiant heater ignition for chair type C, while for chair types A and B the radiant heater ignition is worse. The radiant heater is worse than the match-like source for chair type D, while the match-like source is worse than the radiant heater for chair type C.

Table 5 is a subset of Table 4 presenting the results for the living room/dining room fires only. Here the radiant heater is more hazardous than the gas burner for chair types A, B, and D. The match-like source is more hazardous than the gas burner for chair types B and D Evidently, remoteness from the room of fire origin makes the rapid early spread found with the largest ignition source less relevant in the overall hazard development. Thus one cannot make the generalization that the larger sources are always more hazardous.

Furthermore, as a check on sensitivity to fire room size and total house volume, the living room/dining room fire simulations were re-run after specifying a fire room floor area of half the original size (therefore the local room volume was decreased by half and the total house volume was decreased by 20%). The simulation results are shown in Table 6. The total number of deaths is essentially the same as the original simulations, though there is some shift in scenario/death numbers. Again, the larger source is not necessarily the most hazardous.

TABLE 6
Number of Predicted Deaths from HAZARD I (Fire in Living Room/Dining Room, 1/2 Original Room Size)

Chair type	*Ignition source*					
	B	*H*	*M*	*L*	*C*	Σ
A	0	4	NI[a]	NI	0	4
B	4	6	2	NI	NI	12
C	2	0	4	NI	NI	6
D	2	2	4	4	NI	12
E	2	0	NI	NI	NI	2
Σ	10	12	10	4	0	36

[a] No ignition (i.e. no sustained flaming and thus no deaths).

The results above demonstrate that the potential hazard for a given chair type depends on both the ignition source and the scenario. Therefore, no specific ignition source out of those chosen for this study clearly presents the greatest potential hazard for all chair types in the limited set of fire scenarios considered.

The TB 133 ignition source is the most conservative in the sense that it ignites all of the chair types, and looking at the combined results of Tables 4 and 6, deaths were predicted for all chair types. This suggests that the relatively fast rate of rise to the peak heat release rate seen with the TB 133 ignition source is an important factor in the relative hazard of a given upholstered furniture item.

A sobering observation emerges from an examination of the timing of critical events in the HAZARD I predictions. If one compares the time of earliest occupant alert to the fire with the time at which it is clear that at least one occupant will die (due to entrapment or being left behind leading to death), the time difference is found to be less than 30 s in nearly all cases. These results are tabulated explicitly in Ref. 16. This observation suggests (as did the results from the TB 133 fire simulations) that the rate of rise out to the peak heat release rate is pertinent to the outcome of these simulations since the fate of the occupants was decided in the time period before the peak heat release was realized.

To summarize, these simulations suggest the following:

1. No single ignition source utilized here always presents the greatest potential hazard for all chair types. The hazard depends on the ignition source and the scenario. The TB 133 igniter is the most

broadly conservative, and thus most consistent with normal testing practice.
2. The presence of a working smoke detector has a dramatic impact on the survivability of occupants exposed to the furniture fire scenarios considered here.
3. Rate of heat release is an important parameter. Slow fire growth rates and relatively low peak heat release rates are desirable to reduce the predicted deaths for the scenarios considered here.

We must point out some of the limitations and caveats of the preceding hazard analysis.

- The numerical results are indicative, not representative of statistical fire data. The chair types were picked only to be representative of a wide range of fabric combinations and do not necessarily represent a known cross-section of chairs in use in residences today.
- US fire statistics implicate ignition by smoking materials in a large fraction of upholstered furniture fires where the furnishing was the first item ignited; these statistics also show that fires initiated by smoking materials are a major cause of fire deaths. In the analysis above, the one chair type that did smolder and burst into flames did not kill anyone in the simulations, but that fact is tempered by the realization that only two fire/occupant-set scenarios were considered out of the many identified in the NFPRF report, and the fact that no probability weighting factors for these specific scenarios were attached to the results.
- Toxic potency was not fully addressed since only CO, CO_2 and O_2 species concentrations were predicted. The toxicological impact of other species produced (HCN or HCl for example), in addition to those measured, is not treated, though their effects are not believed to be capable of strongly altering the results here.

CONCLUSIONS

Overall, this study supports the conclusion that the rate of heat release behavior of an upholstered furniture item can be effectively assessed (and its relative hazard as a flaming object inferred) by means of a strong ignition source such as the TB 133 gas burner. This study suggests that the flaming fire hazards of furniture can be minimized by placing limitations on the peak heat release rate plus the speed at which that peak is reached. This joins the reduction in ignition risk, generally from smoking materials, as an effective means to reduce the overall hazard to life and property which furniture fires represent in the USA.

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NOTES

1. The use of an electric spark is an artifice that assures ignition if, indeed, ignition is possible. It is probable that in the real world many exposures of the type used here do not progress to flaming ignition even though a flammable mixture of gases may be produced. Here it was necessary to guarantee ignition of these gases on a reproducible basis.
2. Note that the preceding procedure does not directly simulate what would happen if the light bulb broke on the chair arm. In that case the local ignition source could be expected to be briefer but more intense, possibly igniting other material combinations. The subsequent rate of heat release curve would not be expected to be appreciably influenced by this change in ignition detail, however.
3. For all sources, including those involving either preheating or smoldering, time zero is taken to be the first appearance of flames.
4. HAZARD I contains a very conservative temperature criterion for incapacitation (65°C) and a more realistic thermal dose relationship; only the latter was used here. In the results reported in Ref. 16 the 65°C criterion was used.
5. It is recognized that some of the specific ignition sources/scenarios are inconsistent with all of the occupants being asleep. The goal of assessing the sensitivity of the outcome of an upholstered furniture fire to ignition source is still valid, however.
6. Time-resolved data that are input into HAZARD I are limited to a maximum of 21 points at user specified times. Thus the heat release rate curve was approximated by selecting a limited number of values representative of the curve.
7. A 't^2 fire' is a specified fire in which the heat release rate grows as the square of time. A constant multiplier determines the absolute value, dictated by the fire load.

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