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FURNITURE FLAMMABILITY: AN INVESTIGATION OF THE CALIFORNIA TECHNICAL BULLETIN 133 TEST. PART I: MEASURING THE HAZARDS OF FURNITURE FIRES

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TABLE OF CONTENTS

LISTS OF FIGURES

LIST OF TABLES

Preface

In Fiscal Year 1989 the Congress requested a study on ignition of upholstered furniture. The desire was to provide a sound technical basis for a test method to measure the fire hazard of upholstered furniture subject to flaming ignition. This need was prompted by the increasing concern for fire safety in public occupancies and the development and interest in the use of California Technical Bulletin 133 [17]. The short range objectives of this study are reported in a three part series listed below:

Furniture Flammability: An Investigation of the California Technical Bulletin 133 Test.

Part I: Measuring the Hazards of Furniture Fires, NISTIR 4360, July 1990, by J. G. Quintiere.

Part II: Characterization of the Ignition Source and a Comparable Gas Burner, NISTIR 4348, June 1990, by T. J. Ohlemiller and K. Villa.

Part III: Full Scale Chair Burns, NISTIR 4375, July 1990, by W. J. Parker, King-Mon Tu, S. Nurbakhsh and G. H. Damant (State of California Dept. of Consumer Affairs, Bureau of Home Furnishings and Thermal Insulation).

These reports addressed the following objectives:

1. Identification of the significant measurements needed to characterize the fire hazard of furniture, (Part 1).

2. Development of an alternative ignition source comparable to the Cal. Tech. Bulletin 133 test to insure greater reproducibility, (Part 2).

3. Testing of a wide range of upholstered chairs to refine and improve the measurement techniques of Cal. Tech. Bulletin 133, (Part 3).

Specific results developed in this three part study are summarized below:

* The heat release rate was defined as the major fire hazard of upholstered furniture.

* The TB133 newspaper ignition source was characterized as to exposure area, heat flux and duration.

* A gas burner was designed and characterized as an alternative ignition source.

* A relationship was established between the peak heat release rate criterion for failure of the TB133 test.

* Using this equivalent heat release rate criterion it was shown that TB133 is conservative.

* It was shown that furniture suitable for high risk occupancies has similar heat release rates in the TB133 room, in the proposed ASTM room and in the furniture calorimeter.

* It was demonstrated that HAZARD I can calculate the upper air temperature in the room if the heat release rate of the furniture is known.

* A correlation was developed between the peak heat release rate of the furniture in the furniture calorimeter and the heat release rate per unit area in the cone calorimeter.

The results of these objectives have led to improvements and equivalent alternatives to 133 which are currently being adopted and adapted. Indeed, work is continuing to strengthen the justification of alternative testing strategies without compromising the practical implementation of 133. A special study to more fully examine the effect of the ignition intensity and duration on the fire spread over the chair has commenced. We are also investigating approaches to utilizing small scale component data to complement the need for full scale chair testing. Ultimately, the successful relationship with small scale test data could lead to an economical testing process which would cope with the varieties of fabrics and cushioning materials associated with a given chair. style.

Part I: Measuring the Hazards of Furniture Fires

by

James G. Quintiere

Abstract

The hazards due to furniture fires are examined. These include ignition of an adjoining item, flashover, CO toxicity, and reduced visibility as a result of smoke. Theoretical analyses are given to quantify the hazards, and typical parametric values are given for several materials representative of a range of fire performance. Results are presented in terms of conditions at the flame tip, at the onset of flashover, and for a ventilation-limited fire. Critical hazard measurements are identified, and an illustration is given on how to characterize the hazards. Finally, a critical review of the measurements used in the California Technical Bulletin 133 is made, and recommendations for improvements are offered.

Key words: California Technical Bulletin 133; fire hazard; flashover; furniture; ignition; smoke.

1. Introduction

This report seeks to identify and discuss the potential hazards caused by fire initiated on furniture items in an enclosure. Although this work focuses on upholstered furniture, the analysis and discussion presented can be generally applied to all combustible contents. Moreover, this study was part of a larger investigation to evaluate the performance criteria of California Technical Bulletin 133 [17] and to recommend improved alternatives. Therefore, this report has two parts: (1) a presentation of the measurements needed to characterize the hazards of furniture fires, and (2) the relationship of these measurements to the procedures used in Technical Bulletin 133.

The approach taken was to define distinct hazards associated with furniture fires. The nature and scope of these hazards will determine the needed measurements. We will seek to formulate the measurements in a way that will allow the most general application to analyze the hazard in the context of end use. There may be some degree of arbitrariness to the hazards defined, but they were motivated by our interpretation of the scope of Technical Bulletin 133. In particular, one may wish to consider more comprehensive measurements to represent the potential toxic hazard.

Four hazards are defined and described below:

1. Fire Spread. Given the ignition of an object, we consider that the subsequent ignition and spread to a noncontiguous second object is a hazard.

This allows the fire to increase in size and its potential for continued growth and flashover is enhanced.

2. Flashover. Flashover is the event in the development of a room fire in which the entire fuel contents of the room become involved. The source of the fuel is now indistinguishable among the various furnishings and contents within the room. After flashover the quantity of combustion products is dramatically increased and their nature is significantly changed. Flashover is a serious threat to life safety beyond the room of fire origin, and enhances the growth of fire to other parts of the building. Therefore, the fire conditions of a single item burning which are sufficient to cause flashover is a significant benchmark for hazard.

3. Toxicity. Products of combustion, both gaseous and particulate, can have physical and chemical effects on people that reduce their ability to function leading possibly to incapacitation and death. This is a very complex process involving many potential causes and effects; however, it is well recognized that carbon monoxide (CO) is the principal toxicant in combustion gases for most common fuels. The inhalation of CO over time reduces the oxygen in the blood by forming carboxyhemoglobin (COHb). This causes asphyxiation. We shall only consider the toxic hazard due to CO in our analyses. We recognize that a more complete characterization of toxic hazard is needed, but this would involve understanding the factors responsible for producing other fire products and the means to evaluate their human response.

4. Smoke Obscuration. Particulates produced by the fire and transported by the combustion gases will lead to reduced visibility. This will depend on dilution of the fire gases by air, and the location of the smoke relative to people. The reduction in visibility presents a hazard in retarding and possibly preventing escape.

The scope of the hazard conditions considered above, except for special issues associated with toxicity, is sufficiently comprehensive to evaluate the fire hazards of a single object once ignited. We shall tailor these to the particular application of upholstered furniture, but many aspects of the analysis do not explicitly depend on the nature of the specific object burning. The approach will be to examine the fire conditions necessary to achieve the individual hazards, and to describe the means to quantitatively evaluate the extent of hazard. In short, the level of hazard must be described in terms of measurable fire variables. Finally, we may find that some hazards may be subsumed by others. For example, if it is not likely that smoke visibility is a problem until after flashover, then the measurements necessary to characterize the flashover hazard become most important. Measurements for smoke visibility may be secondary, or not significant. This measurement hierarchy for hazard assessment, is key to achieving an effective and economical test method for the evaluation of furniture flammability performance.

In summary, we will examine the conditions needed to characterize the fire hazard of a single object burning in a compartment to:

- involve other combustible objects;
- cause flashover in the room of fire origin;
- result in incapacitation and death of occupants based on exposure to CO concentration; and
- impair the occupants ability to see the escape route.

2. Fire Hazard Measurements

2.1 Fire Spread

We shall characterize fire spread from a burning object to an adjoining non-contiguous object as due to piloted ignition [1]. From theoretical considerations and data on many materials we can characterize conditions for ignition [2]. Most common combustible materials have a range of ignition temperatures of approximately 300 to 500°C. This would correspond to a minimum or critical radiant heat flux for ignition of approximately 1 to 3 W/cm^2. Below these heat fluxes an object will not ignite and above these heat fluxes the time to ignite will decrease with increasing heat flux. This will depend on its

$$t = \frac{T_{ig} - T_\infty}{\dot{q}''/\rho c \delta}$$

where T_{ig} is the ignition temperature

T_∞ is the initial temperature

$\dot{q}''$ is the radiant heat flux

ρ is the density

c is the specific heat

δ is the thickness.

Let us consider a typical fabric material that might represent a drapery or a thin fabric on an insulating substrate; similar to cushion or upholstered product. Representative properties, for a cotton-like material, are selected as follows:

ρ = 0.57 g/cm^3,
c = 0.34 cal/g-K,
δ = 1 mm.

For T_{ig} = 300°C, ignition times range from 5 to 25 s for a range of radiant heat fluxes between 4 and 1 W/cm^2, respectively. For T_{ig} = 400 °C, these times only increase by about 25 percent. Hence, these objects can ignite very quickly. Flashover conditions are sometimes designated with a heat flux to the floor of 2 W/cm^2 (indicative of room smoke layer temperature of 500-600°C). Hence we see that most thin materials will rapidly ignite under this condition which is consistent with our concept of flashover.

Most materials and products would tend to be characterized as thick, and ignition times can be estimated for them by

$$t = \frac{\pi}{4} \quad k\rho c \left(\frac{T_{ig} - T_{\infty}}{\dot{q}''}\right)^2 \tag{2}$$

The new variable here is k, the thermal conductivity. Light weight foam materials may have $k\rho c$ values as low as 0.01 $(kW/m^2K)^2 s^{-1}$, whereas a value of 1 might be an upper limit for more dense common furnishing and construction materials. For this class of materials we can estimate from Eq(2) or derive from the literature [2] some representative responses. Some examples are listed below:

$\dot{q}'' = 1\ W/cm^2$	$t \sim 300$ s (e.g. PMMA, polyurethane foam, acrylic carpet)*
$\dot{q}'' = 2\ W/cm^2$	$t \sim 70$ s, wool carpet $t \sim 150$ s, paper on gypsum board $t \sim 250$ s, wood particle board
$\dot{q}'' = 3\ W/cm^2$	$t \sim 5$ s, polyisocyanurate foam $t \sim 70$ s, wool/nylon carpet $t \sim 150$ s, hardboard

Hence we see that at 2 W/cm^2, a condition commonly used to imply flashover, it can take one or more minutes to achieve full involvement for common materials. But once room thermal conditions are achieved sufficient to ignite other materials, the transition time for full room fire involvement would be much shorter than these ignition times since the heat fluxes in a room at full involvement will exceed 10 W/cm^2. Thus, the increasing heat fluxes will reduce the times to ignition or flashover.

To put this in perspective relative to human tolerance, a radiant heat flux of 0.4 W/cm^2 will cause pain to bare skin in approximately 30s [8]. Hence it is not likely that people would willingly be exposed to fire radiant heat flux conditions needed for ignition.

Let us now examine the properties of a burning item capable of producing these heat fluxes necessary for ignition. For an upholstered item of furniture the radiant output will depend on the nature of the materials, the construction, and the configuration. It also will depend on the location and orientation of the surface associated with the target object. The simplest representation of this phenomena can be expressed for a point source of radiant energy:

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*These materials are cited to give tangible examples based on test results for specific products. No generalizations should be made.

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi R^2} \quad (3)$$

where $\dot{Q}$ is the rate of energy release of the item

χ_r is the fraction of radiant energy

R is the distance from the point representing the item

and $\dot{q}''$ is the maximum heat flux at distance R.

Modak [3] showed that this formula is accurate to within 80 percent for $R \geq 2R_o$ where R_o is the radius of a circular pool fire. We present this to illustrate the key variables, not as a means to predict the radiant flux from a specific chair fire. Nevertheless, it might be a reasonable first order approximation, if we knew $\dot{Q}$ and X_r for the chair fire. For a typical average value of $X_r = 0.3$ and at a distance of 0.5 m or approximately 1.5 ft, we obtain

$$\dot{q}'' = 10^{-2}\dot{Q}(\mathrm{kW}) \text{ in W/cm}^2$$

which would suggest an energy release rate of 100 kW to begin to pose an ignition hazard at 1 W/cm². Data from a wide range of chair fire experiments show actual values of $\dot{Q}$ ranging from 200 to 700 kW to cause 1 W/cm² at a distance of 0.5 (1.5 ft) from the edge of the chair. The full range of data are sketched in Figure 1. This shows the range of conditions likely to be expected for upholstered chairs. Data from Mizuno and Kawagoe [5] were correlated by

$$\dot{q}'' = 0.031\ \dot{m}/R^{1.8} \text{ in W/cm}^2 \quad (3a)$$

where R is the distance from the chair flame in m and $\dot{m}$ is the burning rate in g/s.

For a heat of combustion of 20 kJ/g and R = 0.5 m,

$$\dot{q}'' = 0.005\ Q(\mathrm{kW}) \text{ in W/cm}^2. \quad (3b)$$

This is the upper limit to the data range in Figure 1, and gives the minimum heat release rates likely to cause ignition of an adjoining item 0.5 m away. This suggests a range of 200 to 400 kW corresponding to 1 to 2 W/cm². It is also interesting to note that a chair fire of approximately 600 kW and 1 m in diameter will likely have its flame reach an 8 ft (2.44m) ceiling [12]. Once the flame reaches the ceiling the radiant heat flux to the region below will be further enhanced; moreover, if the ceiling is combustible it will likely ignite with flame contact. A range of 200 to 400 kW could represent a minimum threshold for ignition of many items at ≤ 1.5 ft and 600 to 1200 kW represents a range where almost any solid item would ignite. The latter values are taken from Figure 1 at 3 W/cm² over the range of data. This gives some upper and lower bounds for performance requirements in terms of energy release rate $\dot{Q}$. A more direct measurement would be to measure radiant heat flux at a specified distance for a specific chair fire. This could be a useful test measurement.

2.2 Flashover

Let us now examine the conditions required for flashover. We use a flashover criteria of a temperature increase of the smoke layer of 500°C. This is approximately consistent with a floor heat flux of 2 W/cm². The layer temperature depends on the energy release rate and on the compartment construction and configuration. An approximate formula in terms of these variables is [6]

$$\Delta T = 6.85 \left(\frac{\dot{Q}^2}{A_o \sqrt{H_o} \ (h_k A)} \right)^{1/3} \text{in °C} \tag{4}$$

where $\dot{Q}$ is in kW
A_o is the doorway area in m²
H_o is the doorway height in m
A is the room surface area
h_k is a heat loss factor taken as 0.021 - 0.042 $\frac{kW}{m^2 K}$

(representative of gypsum board construction and a fire

duration of 100 to 400 s).

For a typical room of height 8 ft (2.44 m) and a door size of 3.2 ft (1 m) by 6.4 ft (2 m) the minimum $\dot{Q}$ values to cause flashover (ΔT = 500°C) have been computed for a range of room floor areas. These results are plotted in Figure 2 for the range of h_k values selected above. One sees that for plausible room sizes of 8 x 8 ft to 20 x 20, the critical energy release rates range from 800 to 2000 kW.

For a specified door size, the maximum energy release rate possible within the room due to induced doorway air flow is determined from the air flow rate ($0.52\ A_o\sqrt{H_o}$ in kg/s) [7] and the fact that the heat of combustion per unit mass of air is approximately 3 kJ/g. For this case of the 2 x 1 m doorway, $\dot{Q}_{max}$ = 4300 kW. Hence for this "typical" room, the energy rates to cause flashover are 2 to 5 times smaller than the energy release rate limit due to ventilation, (provided sufficient fuel exists). At full involvement (associated with a minimum room heat flux condition of 10 W/cm²), for a typical class of materials (heat of gasification of 2 kJ/g, and heat of combustion of 20 kJ/g) we estimate an energy release rate per unit area of 1000 kW/m². This only requires 4.3 m² to be involved to achieve $\dot{Q}_{max}$ = 4300kW. This area is well under what is available to burn in a typically furnished room. Hence, following the onset of flashover associated by the critical $\dot{Q}$ values in Figure 2, we would expect a typically furnished room to easily reach its ventilation limited state. This is likely to lead to a fuel-rich state producing more gaseous fuel than can burn within the room. At this stage of fire development, combustion products spreading through the building will contain many incomplete products of combustion. We will see that this corresponds to a many-fold increase in the yields of CO and smoke particulates.

2.3 CO Toxicity

The toxicity of CO depends on the rate of inhalation and on the lethal or incapacitating levels of COHb for a particular person. For the case of light activity and 60 % COHb for lethality, it can be shown [8] that

$$t = 0.72 \times 10^5 / X_{co} \text{ in minutes} \tag{5}$$

represents the time for lethality for a constant CO concentration (X_{co}) in ppm (1000 ppm = 0.1%). The incapacitation time would be approximately half this value.

Let us examine typical concentrations of CO produced under flaming conditions. We exclude smoldering effects. We will estimate the concentration of CO just at the tip of the flame under conditions where air is readily available to the flame. If this flame just contacts a smoke layer (or a ceiling) and no further air is mixed with the smoke, this concentration would represent the maximum possible CO for a well-ventilated fire. We will consider several materials listed by Friedman [9] suggestive of a broad range of combustion behavior. For these same materials, we also obtained additional data from Tewarson [10]. We assume that 10 times stoichiometric air is entrained up to the flame tip [11]. The CO concentration at the flame tip can be estimated from

$$X_{co} = \frac{\gamma_{co}}{1+10r} \tag{6}$$

where γ_{co} is the yield of CO in g CO per g of fuel mass lost, and r is the stoichiometric air to fuel mass ratio which can be estimated by ΔH/3 kJ/g) with ΔH the heat of combustion.

Results are shown in Table 1.

Table 1. Flame Tip CO Concentrations

	CO/CO_2 [9]	γ_{co} [10]	$\Delta H \left(\frac{kJ/g}{g}\right)$ [10]	X_{co} (ppm)
Wood	0.002	0.004	12.4	94
Polystyrene	0.08	0.06	27.0	660
Polyvinylchloride	0.17	0.063	5.7	3150
Polyethylene (48% chlorinated)	0.27	0.049	7.2	1960

From Eq. (5) and Table 1 we find that the worst case exposure (X_{co} = 3150 ppm) could cause lethality in 22 minutes. For such an exposure to occur, the products of combustion at the flame tip would have to be transported to the victim without further mixing and dilution by air, and retained for 22 minutes. This is an unlikely scenario for small fires, since flames that do not reach the ceiling would have ample opportunity to entrain more air and dilute the CO. Once a flame extends under a ceiling mixing would diminish and this could represent a worst case. A plausible scenario could have these ceiling gases fill the room above the fire through floor openings. If we approximate a chair fire as 1 m in diameter and 2 m below a 2.44 m (8 ft) ceiling, this corresponds to approximately 600 kW [12]. This gives a benchmark for the size fire for which we might begin to examine the CO concentrations at the flame tip in terms of hazard. Data from Table 1 suggest that we might expect lethality times to range from 22 to over 70 minutes.

Let us examine this from another perspective. Consider a fire in the "typical" room as selected in Figure 2. Let us examine the CO hazard of the materials in Table 1 at the critical energy release for flashover. While we can do this for many room sizes, let us take a plausible range of 800 to 2000 kW as found for our 8 x 8 ft to 20 x 20 ft typical room configurations. As noted in section 2.1, these energy release rates might already be judged unacceptable from the standpoint of potential spread to an adjoining item. We also assume steady conditions for the smoke layer which is a conservative assumption for this hazard assessment and is more valid for small rooms. For the doorway of the typical room, the maximum possible air flow rate is 1.44 kg/s occurring at full room involvement. We will estimate it at flashover to be 1.0 kg/s. In general, we can compute the CO concentration in the gases leaving the room as follows:

$$X_{co} = \frac{\gamma_{co}}{(\dot{m}_a/\dot{m}_f + 1)} \qquad (7)$$

where $\dot{m}_a$ is the air flow rate (1kg/s) and $\dot{m}_f$ is the fuel burning rate = $\dot{Q}/\Delta H$. In Table 2 we have computed CO concentrations for the "typical" room with a critical energy release rate for flashover of 1000 kW. We also list the corresponding required fuel surface area (A_f) to support these combustion conditions. (These are based on Tewarson's asymptotic burning rates per unit area [10].) We tabulate the equivalence ratio (ϕ) which represents the ratio

Table 2. CO Concentrations at Typical Flashover Conditions ($\dot{Q}$ = 1000kW, $\dot{m}_a$ = 1kg/s)

	$\dot{m}_f$ (g/s)	A_f (m^2)	X_{co} (ppm)	r (g/g)	ϕ, Equivalence Ratio
Wood	80.6	7.	300	4.1	0.33
Polystyrene	37.0	1.	2100	9.0	0.33
Polyvinylchloride	175.	11.	25,000	1.9	0.33
Polyethylene (48% (chlorinated)	139.	20.	33,000	2.4	0.33

of fuel to air supplied ($\dot{m}_f/\dot{m}_a$) divided by the stoichiometric fuel to air ratio, (1/r). For these cases, at the inception of the flashover process when $\dot{Q}$ = 1000 kW we have 3 times the required stoichiometric air. The onset of flashover has ϕ = 1/3, compared with the ventilation limit, ϕ = 1. After full room involvement, for typical room fuel loadings we would expect ϕ to exceed 1.

Examination of Table 2 shows that the polyvinylchloride and modified polyethylene present serious CO hazards with lethal conditions in 2 to 3 minutes. Also that these materials require extensive involvement (11 to 20 m^2) to attain these conditions. Thus for these apparent extreme cases of incomplete combustion we have both a CO and flashover hazard occurring in approximately the same times. But this assumes that fire can involve these areas of 11 and 22 m^2 respectively. Thus, one can not separate this CO hazard from the potential for fire growth of the material.

Following flashover it is found that the CO concentrations increase significantly regardless of the materials burning. For example Beyler [13] finds that for $\phi \geq 1$, the CO concentrations can reach 23,000 ppm for pine. We also find that in a room fire, involving only wood, that the CO reached 50,000 ppm in a second floor room following flashover on the first floor [14]. This characteristic is common, but we are just beginning to generally recognize it. For example, Belles [15] reports the case of flashover in a furnished room. The fire was initiated by a smoldering chair which eventually broke into flames. The CO concentration rose sharply just before flashover subsequently reaching a maximum of 70,000 ppm. This is sketched in Figure 3.

Thus we might conclude that before flashover, CO production can be attributable to the material. Following flashover with the occurrence of a ventilation limited fire, CO concentrations would be high enough to produce lethality in less than 3 minutes. Moreover diminished oxygen and high CO_2 concentrations in the combustion product atmosphere would only exacerbate this hazard. For flames with ample air available even the worst CO producers do not present a serious CO hazard as shown by Table 1. However, at the outset of flashover some of these materials can be CO hazards provided a relatively large amount can burn.

2.4 Smoke Obscuration

We shall follow a parallel approach for smoke compared to our CO analysis. We examine the output of a well ventilated flame, the conditions of obscuration at the onset of flashover, and the results expected for a ventilation limited fully involved room fire. We shall use the same materials of Tables 1 and 2 since these appear to span the range of smoke properties for most materials for which data exists. It is interesting to note that CO and smoke production tend to correlate.

Smoke obscuration is measured by the attenuation of a visible light beam. In the fire literature [16] it has come to be expressed in terms of optical density (D) per unit path length measured (L). If I_o is the initial intensity of light and I is the attenuated value, then

$$\left(\frac{D}{L}\right) = \left(\frac{1}{L}\right) \log (I_o/I). \tag{8}$$

Opacity is a measure of smoke obscuration over a given path length.

$$\text{Opacity} = \frac{I_o - I}{I_o} \times 100\% \tag{9}$$

Whereas opacity describes smoke obscuration for a specific path length, D/L has been found to relate directly to visibility. The relationship depends on the nature of the object viewed, but its approximately

$$L_v = \frac{2}{D/L} \tag{10}$$

where L_v is the distance over which the eye can still effectively discriminate objects. For a steady flow system such as the flow at the flame tip, or the smoke leaving a room, we can express (D/L) by

$$\frac{D}{L} = \rho D_m/(\frac{\dot{m}_a}{\dot{m}_f} + 1) \tag{11}$$

where ρ is the density of the exit gases

D_m is the mass optical density, a measurable property

of the smoke.

We shall take $\rho = 1\ kg/m^3$ to compute D/L for smoke that has cooled to ordinary room temperature. For the flame tip case, we take $\dot{m}_a/\dot{m}_f = 10\ r$ as in Eq. (6), and for the case of flashover corresponding to $\dot{Q} = 1000$ kW and $\dot{m}_a = 1$ kg/s we take values for $\dot{m}_f$ from Table 2. The results of these calculations are shown in Table 3. It is obvious from the results that even burning in conditions of

Table 3. Smoke Visibility at the Flame Tip and Flashover Conditions

	D_m [10]	Flame Tip		Flashover at $\dot{Q}$ = 1 MW, $\dot{m}_a$ = 1 kg/s	
	(m^2/g)	D/L (m^{-1})	L_v (m)	D/L (m^{-1})	L_v (m)
Wood	0.037	0.88	2.3	2.8	0.72
Polystyrene	0.335	3.7	0.54	12.0	0.17
Polyvinylchloride	0.400	20.0	0.10	60.0	0.03
Polyethylene (48% chlorinated)	0.342	13.7	0.15	42.0	0.05

ample air, some materials produce smoke that presents the potential for a smoke visibility hazard. For the polyvinylchloride data it would take a dilution rate of 10 times more air to bring the flame tip smoke to a visibility of 1 m, and 30 times (or 30 kg/s of fresh air) more air for the flashover case. These results are consistent with observations of room fire experiments in which visibility can be significantly diminished before flashover begins. However, once flashover leads to a fully involved room fire, we expect D_m values for this air limited situation ($\phi \geq 1$) to attain values between 0.2 and 0.6 m^2/g [10]. Applying Eq. (11) with $\dot{m}_a/\dot{m}_f = r$ ($\phi = 1$) for the range of fuels we have been considering yields visibility levels of 0.0001 to 0.10 m at most. Hence if flashover leads to a ventilation limited fire, which is generally the case for typically furnished rooms, we would expect smoke visibility to diminish significantly .

3. Range of Possible Fire Hazard Conditions

Let us try to summarize and put in perspective some of the results obtained. We have considered four distinct fire hazards: spread to another item, flashover, CO toxicity and smoke visibility. We have introduced ways to characterize these hazards in terms of materials data, and we have reviewed results for a range of materials selected to cover variations among most common materials. We have also examined stages of a fire's development from a well-ventilated flame to the conditions necessary for flashover. Following flashover we examined the consequences of a ventilation limited fire. Hazard assessments can be made for the outputs of each fire stage. But in general hazard must be judged within the context of a particular room or building configuration. We selected a set of "typical" room configurations. For this summary, we will consider only one configuration, but it must be realized that fire hazard must be judged in the context of application and occupancy. However, in considering moveable items, such as furniture, their room setting may not be easily definable. Hence a plausible case may need to serve as the basis for setting performance criteria.

Figure 4 displays a summary of our results. We consider three cases: (1) The well-ventilated fire, (2) the onset of flashover, and (3) post flashover or the ventilation limited fire.

(1) The well-ventilated fire is based on the flame tip analysis in which we explicitly consider the flame tip just reaching an 8 ft ceiling. The energy release rate of such a flame from an item centered 1.5 ft above the floor is approximately 600 kW. This flame is capable of igniting materials 1.5 ft (0.5 m) away. CO toxicity is not a significant factor except for the worst materials which would result in lethality in 22 minutes. Smoke visibility could also be a problem for the worst materials. For this well-ventilated fire we characterize its state of combustion by an equivalence ratio (ϕ) of 0.1, meaning we have 10 times stoichiometric air to burn all of the fuel.

(2) Our flashover case is for a typical room of 10x10x8 ft high with a 3.2 x 6.4 ft high doorway. Flashover would be initiated by a fire of 1000 kW. This particular fire's ventilation state has a ϕ = 0.33. Smoke visibility is likely to be below 1 m, and CO toxicity can lead to lethality in 2 minutes for some materials. These worst case materials (eq. polyvinylchloride from our example) required significant amounts to be involved to achieve the energy release rate requirement for flashover. This implies that by reducing the heat of combustion, the yield of CO (and smoke) increased as a consequence of incomplete combustion. Thus, judging performance on energy release rate alone is not necessarily sufficient to assess hazard.

(3) Having achieved flashover, a fully involved ventilation limited room fire is very likely. This we see is the most hazardous of all three cases with respect to CO and visibility. Also spread beyond the compartment would be very likely.

4. Measurements to Characterize Hazards

This analysis should provide a framework for identifying the needed measurements to assess the fire hazards of furniture for a specific application. It is critical to be able to generalize the measurements to configurations beyond the test configuration. At the current time the most practical way to present this information is in terms of "generation" rates of energy and combustion products. More fundamental measurements in terms of properties, such as heat of combustion or combustion product yields, would require a means to predict the burning rate of the item tested. For a furniture item, this is not possible with current technology. But a burning rate prediction would be essential for effective product development for meeting fire safety performance standards. Moreover, burning rate would depend on the nature and size of the ignition source. This aspect of hazard assessment has not been addressed since we have implicitly assumed to be examining the case of a specific ignition scenario. Also it should be clear from this analysis that hazard must be considered in the context of application and configuration of the building.

For illustration, we present the measurements required in terms of a selected performance level. This level must be set by judgment and the degree of safety required. Also an explicit safety factor may want to be considered in setting these levels, along with feasible levels of product performance. Let us consider each hazard.

1. Spread to an adjoining item.

   Measurement: Heat flux ($\dot{q}''$) at a specified distance. e.g. From Figure 1 we select 2 W/cm^2 to be maintained for 2 minutes to cause ignition of most materials.

   Alternatively, this level would correspond to an energy release rate of furniture items of 400 to 1000 kW at a distance of 1.5 ft (0.5 m).

2. Flashover

   Measurement: Energy release rate ($\dot{Q}$) for a specified time.

   e.g. For our selected typical room (10 x 10 x 8 ft with a 3.2 x 6.4 ft door) we select 800 to 1200 kW for a duration of 2 minutes.

3. CO toxicity

   Measurement: Rate of generation of CO ($\dot{m}_{co}$) for a specified time.

   e.g. For a 2 minute exposure we need X_{co} = 36,000 ppm. For a room with our 3.2 x 6.4 ft door we estimate the corresponding CO generation as from Eq. (7)

$$\dot{m}_{co} = \gamma_{co}\ \dot{m}_f \approx \dot{m}_a\ X_{co} = (1000\text{g/s})(0.036) = 36 \text{ g CO/s}$$

4. Smoke Visibility

   Measurement: Rate of Smoke Obscuration ($D_m \dot{m}_f$) for a specified time.

   e.g. For visibility of 1 m, and a fire in a room with a 3.2 x 6.4 ft doorway, we can estimate from Eqns. (10) and (11)

$$D_m\ \dot{m}_f \approx \left(\frac{\dot{m}_a}{\rho}\right)\left(\frac{2}{L_v}\right) = \left(\frac{1 \text{ kg/s}}{1 \text{ kg/m}^3}\right)\left(\frac{2}{1}\right) = 2 \text{ m}^2/\text{s}$$

Thus, we have developed a set of procedures needed to characterize the hazards. The performance levels indicated above are intended to be illustrative and do not represent recommendations for standard practice.

5. Relationship to California Technical Bulletin 133

We close this analysis by commenting on the hazard levels set in the California Bureau of Home Furnishings and Thermal Insulation Technical Bulletin 133 [17]. The furniture item is burned in a corner of a room constructed of gypsum board which is 10 x 12 x 8 ft high with a doorway 3.1 x 6.8 ft high. This is very close to one of our "typical" rooms and is labeled in Figure 2 to suggest a flashover $\dot{Q}$ = 1100 kW ± 150 kW. Failure in the California test is achieved by exceeding any of the following criteria:

(1) Temperature increase of 200F (111°C) in the smoke layer near the ceiling.

By Eq. (4) it is estimated that this corresponds to an energy release rate of 100 ± 20 kW. A thermocouple in the doorway smoke flow would be a more representative temperature for estimating energy release rate, and our $\dot{Q}$ estimate could be high because the test thermocouple is directly over the fire.

(2) Temperature increase of 50°F 3 ft from the fire at the 4 ft height.

One might suggest this measurement could assess the fire spread hazard potential. But this measurement of gas temperature can be subject to potentially wide variations with respect to the energy output of the fire. First, thermal radiation will cause a response of this thermocouple. The magnitude of that response depends on the heat flux and the local gas velocity. Hence, this measurement can not serve as a substitute for a radiant heat flux measurement. Second, the 4 ft height is a height in the room subject to the greatest gradient in temperature and combustion product concentrations. It is in the transition region between the hot stratified smoke leaving the room and the air drawn into the room. This transition interface region is likely to vary between 2 to 6 ft from the floor depending on the fire size. Consequently, this measurement is not of significant value.

(3) Smoke opacity of 75% at the 4 ft height and 50% at the floor level.

Based on the 12 ft light beam path length of 133, we can convert these opacities to visibility lengths from Eqns (10) and (11). These are, respectively, 40 and 80 ft. Although these values suggest a very severe criteria for hazard, the placement of these smoke meters is not appropriate for characterizing the smoke produced by the fire. Smoke at these locations is very dependent on the mixing conditions in the room. Furthermore, these mixing conditions are a consequence of secondary flows which are not well understood. Nevertheless their locations may have been motivated by a desire to reflect the conditions of exposure to people escaping under a smoke layer. However it should be realized that smoke produced in a fire can quickly fill an adjoining corridor, or the room above. Hence we need to measure the smoke directly in the combustion gases flowing from the fire. Then for the fire application under consideration, we can set our hazard level based on dilution of this smoke relative to location of people who have the risk of exposure.

Consequently, a smoke measurement in the combustion product flow with a shorter path length should be considered.

(4) Carbon monoxide concentration of 1000 ppm in the smoke layer near the ceiling over the fire.

This measurement is similar to the values we computed for the flame tip analysis. As long as flames do not impinge on the ceiling this measurement is representative of the smoke layer or fire's output. By Eq. (5), this level corresponds to lethality in 72 minutes or incapacitation in 36 minutes.

(5) Weight loss criteria are 10% in the first 10 minutes, and 90% by the end of the test.

It is not clear what the significance of these are relative to hazard. Total mass loss could relate to the duration of burning, but it would be more appropriate to consider durations in conjunction with energy and combustion product generation rates. Percent weight loss criteria are not of obvious significance.

From this analysis we can draw the following conclusions with respect to Technical Bulletin 133:

1. The test failure requirements would give a high degree of safety.

2. At this level of safety ($\dot{Q} \leq 100 \pm 20$ kW) we would expect that few materials would present a severe hazard with respect to CO toxicity, smoke obscuration, and flashover would be impossible for practical room configurations.

3. Improvements can be made by taking measurements of temperature, CO and smoke in a well-mixed region of the combustion products flowing from the 133 room. In particular, the current smoke measurements need to be modified. These measurements can be related to more preferred results given as generation rates. A further improvement could be achieved by monitoring the mass flow rate and oxygen depletion of the combustion products along with smoke and CO.

4. The weight loss criteria should be re-evaluated and the introduction of a burning duration in association with the hazard levels be considered.

5. The 4 ft thermocouple measurement should be replaced by a heat flux measurement.

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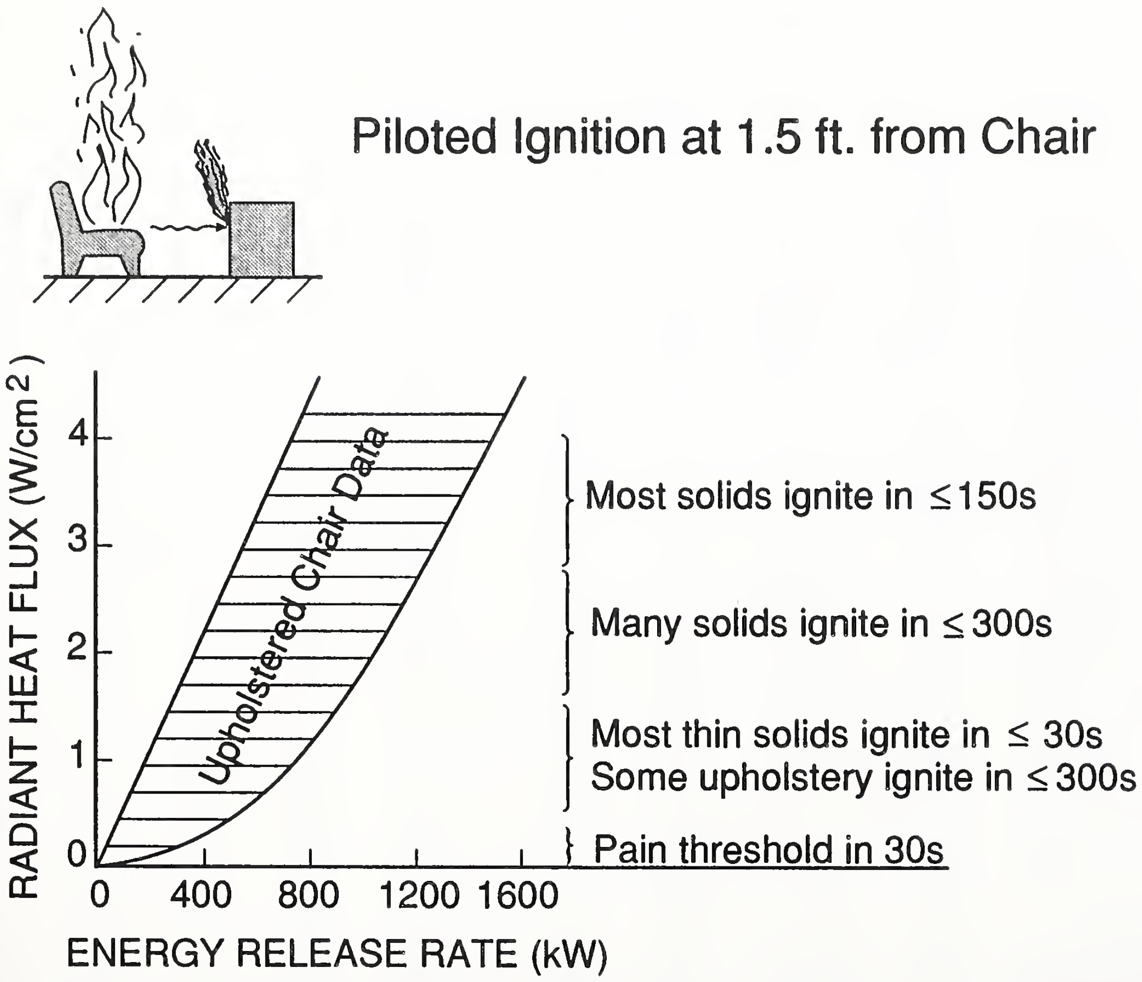


Figure 1. Radiant heat flux to cause piloted ignition in terms of energy release.

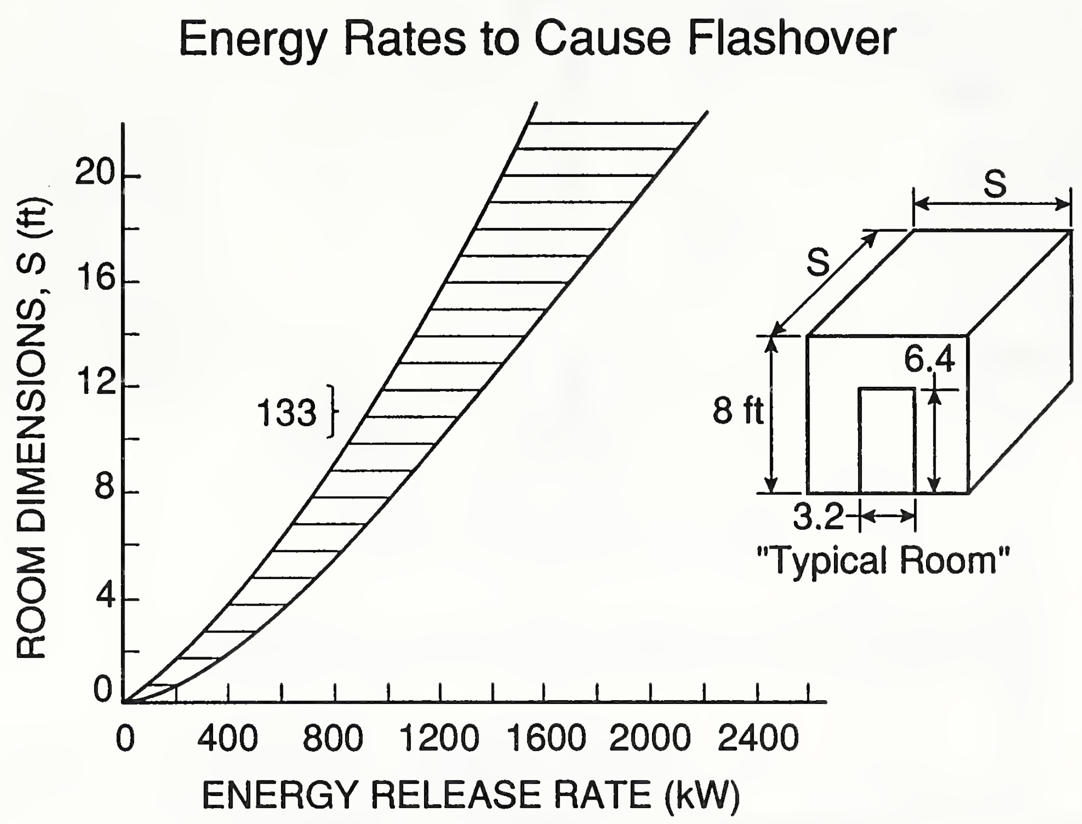


Figure 2. Energy release rates at the onset of flashover for a "typical" room.

Figure 3. <u>FURNISHED ROOM FIRE</u> initiated by a smoldering upholstered chair (D.W. Belles, Fire Journal - March 1985)

Room: 12 x 18 x 8 ft. high; open doorway

Data at 5.5 ft. height

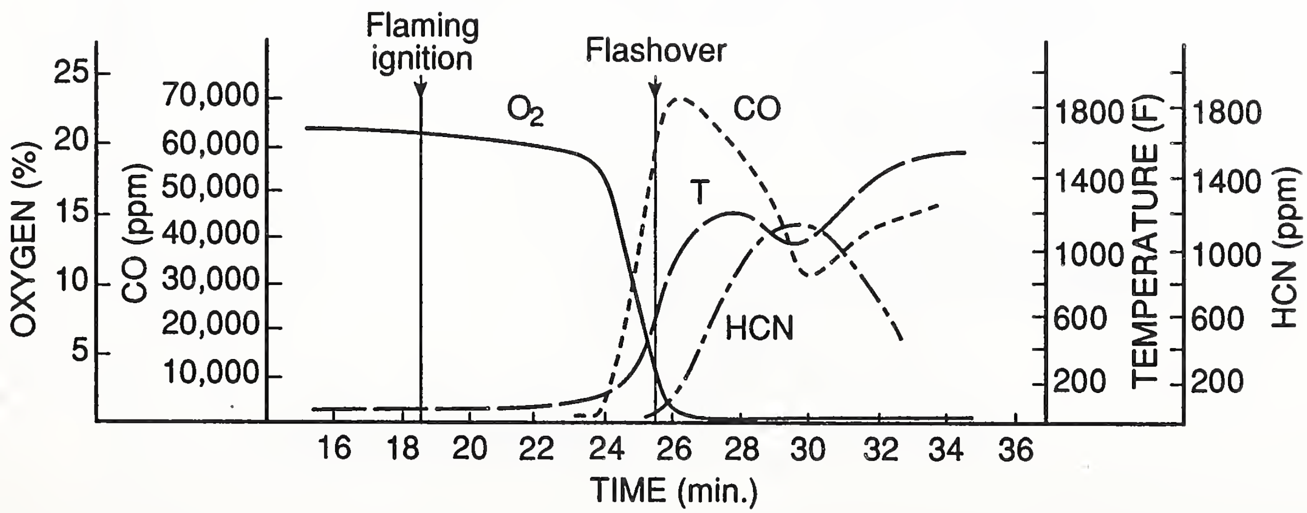
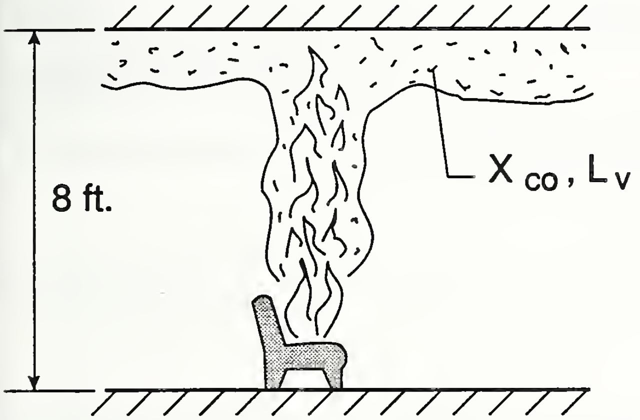


Figure 4. **Range of Possible Fire Conditions**

$\dot{Q}$ ~ Energy Release Rate;
X_{co} ~ Carbon Monoxide;
L_v ~ Visible Length

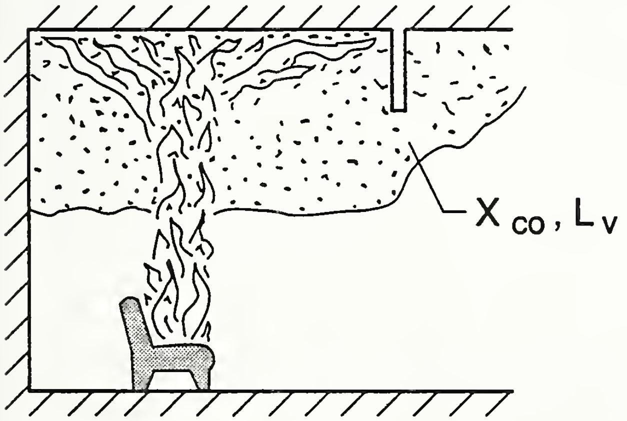
- Well-ventilated fires (ϕ = 0.1, 10 times stoichiometric air)



Flame tip at ceiling, $\dot{Q}$ ~ 600 kW

X_{co} ~ 100 to 3000 ppm
L_v ~ 0.1 to 2.5 m

- Initiation of flashover in a 10x10x8 ft. high room with a 3.2 x 6.4 ft. doorway (ϕ = 0.33, stoichiometric air)



$\dot{Q}$ ~ 1000 kW
X_{co} ~ 300 to 30,000 ppm
L_v ~ 0.03 to 0.7 m

- Ventilation limited fire following flashover ($\phi \geq 1$, less than or equal to stoichiometric air)

$\dot{Q}$ ~ 4500 kW
X_{co} ~ 20,000 to 70,000 ppm
L_v ~ 0.001 to 0.1 m

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

The hazards due to furniture fires are examined. These include ignition of an adjoining item, flashover, CO toxicity, and visibility as a result of smoke. Theoretical analyses are given to quantify the hazards, and typical parametric values are given for several materials representative of a range of performance. Results are presented in terms of conditions at the flame tip, at the onset of flashover, and for a ventilation-limited fire. Critical hazard measurements are identified, and an illustration is given on how to characterize the hazards. Finally, a critical review of the measurements used in the California Technical Bulletin 133 is made, and recommendations for improvements are offered.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

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