
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, CO₂, and O₂

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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 O₂, CO₂, and CO measurements permitted the heat release to be

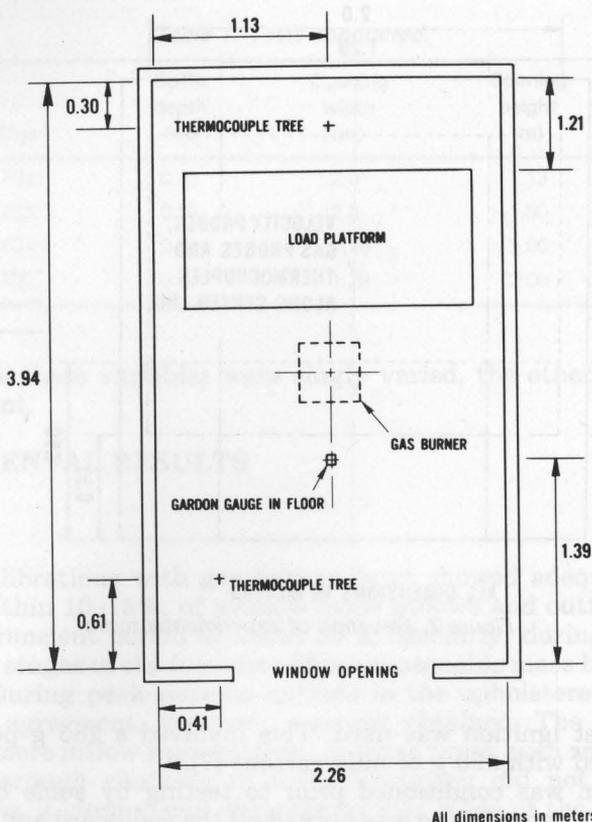
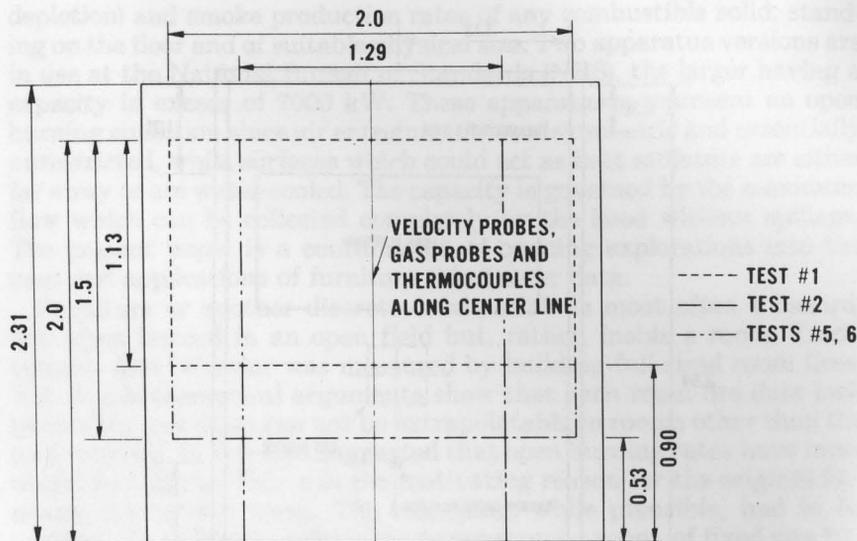


Figure 1. Plan view of experimental room (window opening dimensions indicated in Figure 2).

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).

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 pro-

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

vided where these variables were singly varied, the other two being held constant.

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,

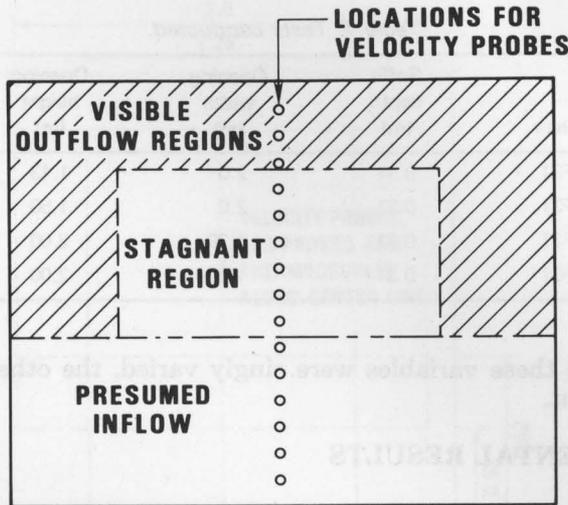


Figure 3. Visual observations of flow at the window opening.

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 $d(\rho V)/dt$. 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.

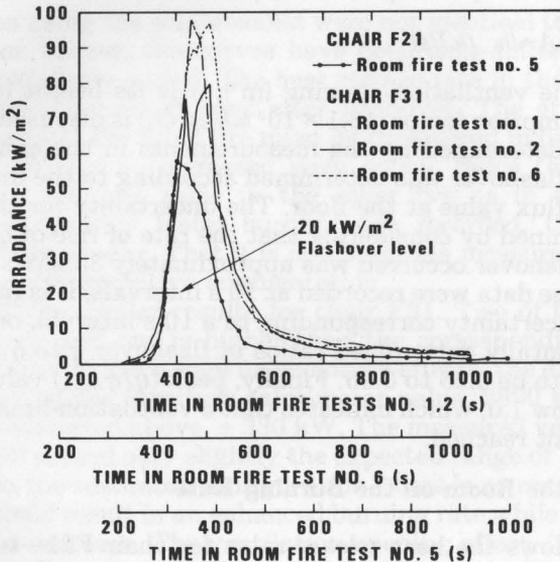


Figure 4. Irradiance measured at floor level.

Table 2. Results of measurements.

Test	Stoich. \dot{q} (kW)	Peak \dot{q}^a (kW)	Peak Floor Irrad. (kW/m ²)	Flashover ^b		Flashover \dot{q} ÷ Stoich. \dot{q} (—)	Peak \dot{q} ÷ Stoich. \dot{q} (—)
				Time (s)	Measured \dot{q} (kW)		
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]

$$\begin{aligned} \dot{q}_{stoich} &= 13.1 \times 10^3 \left(\frac{kJ}{kg O_2} \right) \cdot 0.232 \left(\frac{kg O_2}{kg air} \right) \cdot 0.5 A \sqrt{h} \left(\frac{kg air}{s} \right) \\ &= 1520 A \sqrt{h} \text{ (kJ/s)} \end{aligned}$$

where A is the ventilation opening (m²), h is its height (m), and the oxygen consumption factor (13.1×10^3 kJ/kg O₂) 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

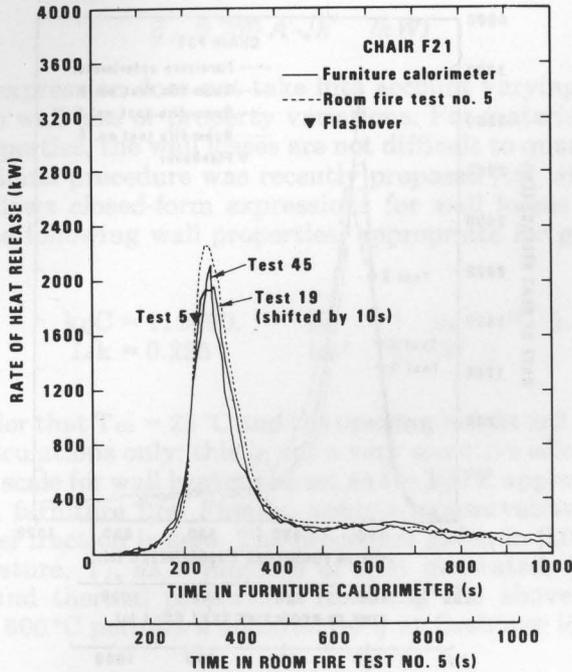


Figure 5. Rate of heat release for chair F21.

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 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

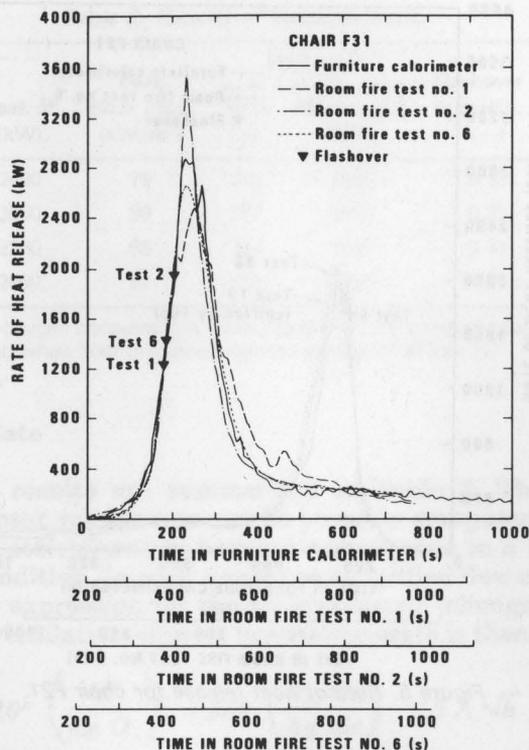


Figure 6. Rate of heat release for chair F31 (loveseat).

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 $T_f = 600^\circ\text{C}$, or a floor irradiance $\dot{q}'' = 20 \text{ kW/m}^2$ 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 stoichiometric 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

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

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 wall-board:

$$\begin{aligned} k\rho C &= 112800. & (\text{J}^2 \cdot \text{s}^{-1} \cdot \text{m}^{-4} \cdot \text{C}^{-2}) \\ L/k &= 0.235 & (\text{m}^2 \cdot \text{C} \cdot \text{W}^{-1}) \end{aligned}$$

Also, consider that $T_\infty = 25^\circ\text{C}$ 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 $T_f = 600^\circ\text{C}$ permits a solution for \dot{q} at flashover (\dot{q}_{fo}) to be obtained:

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

1520

$$(2)$$

This can be solved in the form

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

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

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

Hägglund's recommendation [12] can be expressed as

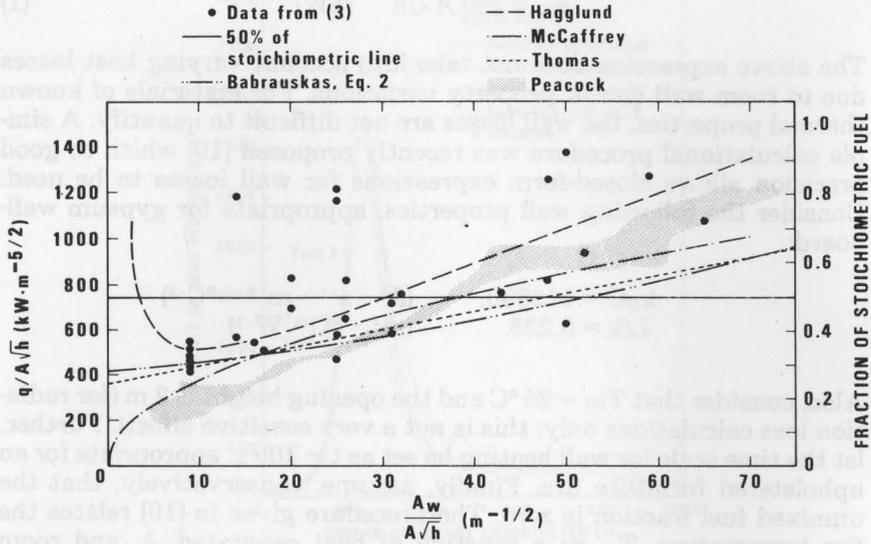


Figure 7. The effect of room wall area (gypsum walls) on the heat required for flashover.

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

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

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

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 $A_w/A\sqrt{h} \leq 30$ 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 in-

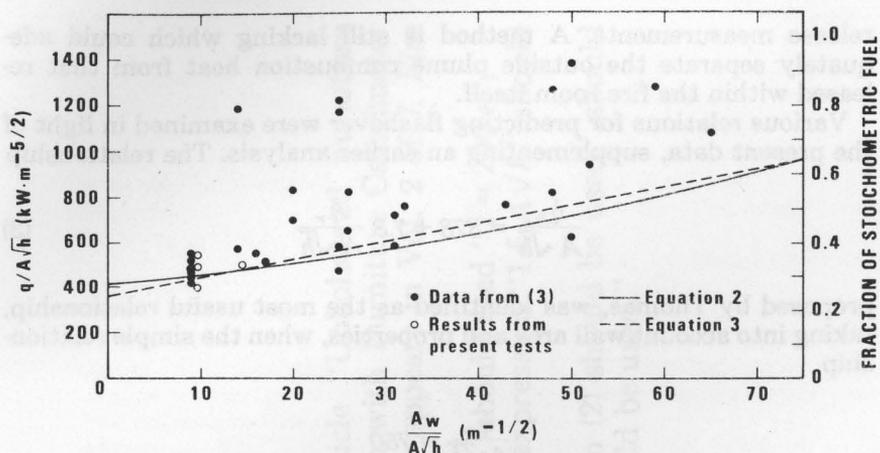


Figure 8. Results from present tests compared to theoretical expressions.

finity, 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.

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 pre-flashover 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

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

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.

in reference 10

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NOMENCLATURE

A	Area of ventilation opening (m ²)
A _w	Area of walls (m ²)
C	Heat capacity (J·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)
\dot{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 · m ⁻³)

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ERRATA

Following are corrections for the article "Upholstered Furniture Room Fires—Measurements, Comparison with Furniture Calorimeter Data, and Flashover Predictions," which appears in Vol. 2 of *J. Fire Sciences*, pp. 5-19 (Jan./Feb. 1984).

On p. 15, second paragraph, " $t = 100$ s" should read " $t = 200$ s".

In the denominator of Equation (2) the expression " $1.5 A\sqrt{h}$ " should read " $1520 A\sqrt{h}$ ".

On p. 18, second paragraph, "Equation (2) should be used" should read "the equation in Reference [10] should be used."